Analyzing Drivers' Responses to Portable Changeable Message Signs in Rural Highway Work Zones

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ABSTRACT

The number of work zones has been increasing in the highway system of the United States because of rising needs in highway construction and maintenance. Highway work zones disrupt normal traffic flow and create safety problems. To improve safety by reducing the risk of vehicle crashes, temporary traffic control devices have been developed and implemented in work zones. A Portable Changeable Message Sign (PCMS), one of the temporary traffic control devices, is capable of displaying a variety of messages to inform motorists of unusual driving conditions in highway work zones. To better utilize a PCMS in work zones, there is a need to investigate the effectiveness of a PCMS and determine the optimal deployment location of a PCMS in the work zones.

The primary goals of this research project were to determine the effectiveness of a PCMS on reducing vehicle speeds and the optimal deployment location of a PCMS in the upstream of one-lane two-way rural highway work zones using the field experiments and survey methods. A slower vehicular speed allows for greater reaction time to avoid crashes, and potentially creates a safer environment for drivers and workers in the work zones. Vehicles were divided into two categories, namely passenger cars and trucks. To accomplish the goals of the research project, the following main tasks were performed: 1) determining the effectiveness of a PCMS on reducing passenger cars and trucks speeds under three conditions (PCMS On, Off, and Absent) using field experiments, 2) developing vehicle speed profile models, 3) using the speed profile models and measured mean speeds to determine the optimal deployment range of a PCMS in the upstream of work zones, 4) investigating drivers' reactions after seeing a PCMS using the survey method, and 5) comparing the speed reductions of passenger cars and trucks to determine

if a PCMS could be utilized to reduce the risks of truck-related crashes in one-lane two-way rural highway work zones.

Utilizing the findings of this research project, traffic engineers will be able to determine if, where, and how a PCMS needs to be deployed in one-lane two-way rural highway work zones to mitigate vehicle crash risks. As a result, the safety of work zones will be improved and resources will be better utilized.

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CHAPTER 1: INTRODUCTION

1.1 PROBLEM STATEMENT

The United States made an extraordinary capital investment in highways from the 1950s to 1970s by constructing the Interstate Highway System and many other roadways. Most of the U.S. highways were designed with pavements that were expected to last 25 to 30 years before major rehabilitation was necessary. As a result, most highways in the nation's highway system currently need renewal, which means public travelers are encountering many work zones on highways. "A highway work zone is an area of highway with construction, maintenance, or utility work activities" (FHWA 2009c). It can be divided into four areas: the advance warning area, the transition area, the activity area, and the termination area (FHWA 2009c).

The appearance of work zones in highways disturbs regular traffic flow, causes traffic congestion and delay, and thus, creates safety problems. Since the 1960s, highway work zone safety has become a research focus and many researchers have published their findings on this subject. However, despite the efforts made so far, highway work zone safety remains unsatisfactory nationwide. Figure 1.1 shows a ten-year trend of work zone fatalities in the United States from 2000 to 2009 (FHWA 2009a). From the illustration, the nation's death toll from work zone crashes climbed to a peak of 1,181 at 2002. Although the number dropped slightly in the following years, there were on average more than 965 people killed in work zone crashes each year during this period. In addition to fatalities, there were about 40,000 people injured due to vehicle crashes in work zones each year (FHWA 2009b). The alarming numbers indicate a need to continuously improve work zone safety nationwide.

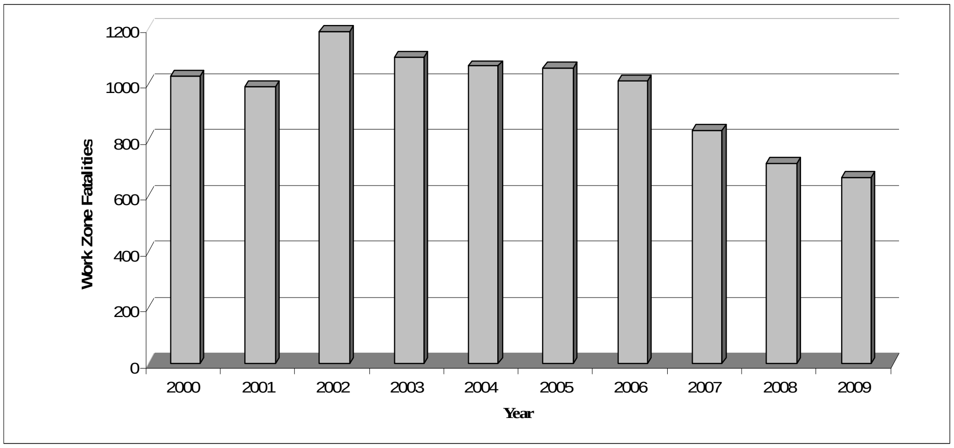


Figure 1.1 Ten-Year (2000-2009) work zone fatality trend

Work zone safety has been a high-priority issue for engineering professionals, government agencies, and the highway industry for decades. At the national level, emphasis on work zone safety has increased by legislation. In Section 1051 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, the Secretary of Transportation was required to develop and implement a work zone safety program which would improve work zone safety at highway construction sites by enhancing the quality and effectiveness of traffic control devices, safety appurtenances, traffic control plans, and bidding practices for traffic control devices and services (FHWA 1991a). In Section 2002a, the Secretary was required to develop uniform accident reporting for fatalities, injuries and certain specified accident types, including highway construction site accidents (FHWA 1991b). The National Transportation Safety Board (NTSB) issued a report on June 3, 1992 which included two recommendations concerning the reporting of work zone accidents: 1) Recommendation H-92-032: “the reporting of work zone fatalities should be revised to distinguish between persons driving highway maintenance vehicles within work zones and other drivers who crash in work zones while traversing the work zone site" (NTSB 1992); 2) Recommendation H-92-033: in conjunction with the Federal Highway Administration (FHWA) all state accident report forms should be reviewed and the data elements that comprehensively document work zone accidents should be identified, and States should be encouraged to incorporate these data elements into their accident report forms (NTSB 1992). The recent Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) included a number of provisions emphasizing highway work zone safety and other work zone-related issues (FHWA 2005). "The FHWA and the American Association of State Highway and Transportation Officials (AASHTO) have played leading roles on this subject and have developed practical highway work zone safety guides and programs" (Bai and Li 2007). For example, to collect and report the data of death and injuries in highway work zones crashes, the FHWA developed guidelines in cooperation with the National Highway Traffic Safety Administration (NHTSA). Also, the FHWA worked with state highway agencies on evaluating programs to collect and analyze work zone crashes and data.

To improve the safety of work zones, numerous traffic control devices (TCDs) and other safety features on or adjacent to travel lanes have been developed and implemented nationwide. The 2009 version of the Manual on Uniform Traffic Control Devices (MUTCD) and its periodic revisions represent the results of years of experiments and are the national engineering standard for highway traffic control. Regarding work zones, to provide reasonably safe and efficient traffic flow during road works, temporary traffic control (TTC) devices are utilized during road construction and maintenance. According to the MUTCD, TTC devices that are commonly used in work zones include flaggers, traffic signs, arrow panels, channelizing devices, pavement markings, lighting devices, temporary traffic control signals, rumble strips, and portable changeable message signs (FHWA 2009c).

A Portable Changeable Message Sign (PCMS), sometimes referred to as a Changeable Message Sign (CMS), a Variable Message Sign (VMS) or a Dynamic Message Sign (DMS), is a traffic control device capable of displaying a variety of messages to inform motorists of unusual driving conditions. The PCMS can not replace any of the signing detailed in the MUTCD; it is a supplemental device to standard traffic control signs. Like any kind of TTC devices, understanding the effectiveness of a PCMS is important for traffic engineers to design the work zone layout. With the development of computer science, some researchers tested the effectiveness of PCMS under a simulated driving environment rather than in a real life situation. As is commonly known, the simulation study had its limitations. To better utilize the PCMS in work zones, field studies of the effectiveness of a PCMS are needed. Results of such studies hold a promise to further improve highway work zone safety.

1.2 DISSERTATION OGRANIZAITON

This dissertation includes eight chapters. The first chapter is the Introduction. The remaining chapters are described as follows:

Chapter 2: Objectives, Scope, and Methodology

This chapter states the primary objectives of this research. The scope and methodology of this research are also described in this chapter.

Chapter 3: Literature Review

This chapter states the findings from a comprehensive literature review. The literature reviewed includes previous analyses of crashes in highway work zones, traffic control methods in work zones, truck safety, statistical methods used in work zone safety analysis, and research development trend in work zones.

Chapter 4: Field Experiment Phase I

This chapter describes the field experiment Phase I including experimental setup, data collection, and data analysis. The purpose of experiment Phase I was to determine the effectiveness of a PCMS on reducing vehicle speeds in the upstream of work zones.

Chapter 5: Field Experiment Phase II

This chapter describes the field experiment Phase II, which was conducted to determine the optimal deployment location of a PCMS in the upstream of highway work zones.

Chapter 6: Field Experiment Phase III

This chapter describes the field experiment III, which was conducted to validate the optimal deployment location of a PCMS and determine the vehicle speed profiles in the upstream of work zones.

Chapter 7: Speed Reduction Comparison between Passenger Cars and Trucks

This chapter presents the results of data analyses on the speed reduction difference between passenger cars and trucks when using a PCMS in the upstream of work zones. The findings of this chapter were helpful for further researches which focus on mitigating severity of truck-related crashes in work zones.

Chapter 8: Conclusions and Recommendations

This chapter presents research conclusions and proposes recommendations for future highway work zone safety research.

CHAPTER 2: OBJECTIVES, SCOPE, AND METHODOLOGY

2.1 RESEARCH OBJECTIVES

The primary goals of this research project were to determine the effectiveness of a PCMS on reducing vehicle speeds and the optimal deployment location of a PCMS in the upstream of one-lane two-way work zones in rural highways. The vehicles will be divided into two categories, namely passenger cars and trucks. “The passenger-car class includes passenger cars of all sizes, sport/utility vehicles, minivans, vans, and pick-up trucks” (AASHTO 2004); the length of the passenger-car class is 19 ft or less (AASHTO 2004). All other vehicles whose lengths are longer than 19 ft are treated as trucks. The goals of the research project were realized through achieving specified research objectives using field experiments and survey methods. The objectives are described as follows:

1. To design the field experimental layout for the determination of the effectiveness of the PCMS;
2. To conduct field experiments under three conditions: 1) the PCMS turned on (PCMS on), 2) the PCMS turned off, but still visible (PCMS off), and 3) the PCMS was out of sight (PCMS absent);
3. To analyze the experimental data to determine the effectiveness of the PCMS on reducing speeds of passenger cars and trucks;
4. To develop models of vehicle speeds in the upstream of one-lane two-way work zones when the PCMS is active, then using the models and measured

mean speeds to determine the optimal deployment location of a PCMS in the upstream of work zones;

5. To validate the optimal deployment location of a PCMS by conducting additional field experiments under the condition of placing the PCMS within the range of the optimal deployment location;
6. To investigate the impact of the PCMS on drivers' behavior in the upstream of one-lane two-way work zones using the survey method;
7. To investigate the speed reduction difference between passenger cars and trucks when using a PCMS in the upstream of work zones.

The effectiveness of the PCMS on passenger cars and trucks was separately analyzed because drivers of these two types of vehicles might react to the PCMS differently. Besides the field experiments, the drivers' survey was conducted and analyzed systematically. The results of the survey could be used to better understand the effectiveness of the PCMS in one-lane two-way rural highway work zones. The developed speed models in the upstream of work zones were utilized to discover the relationship between the work zone design variables and vehicle speed variations with the purpose of reducing crash risks. Utilizing the findings of this research project, traffic engineers will be able to determine if, where, and how a PCMS should be deployed in one-lane two-way work zones to mitigate vehicle crash risks. As a result, the safety of work zones will be improved and resources will be better utilized.

2.2 RESEARCH SCOPE

The scope of this research was limited to the study of the PCMS on vehicle speed changes in one-lane two-way rural highway work zones in Kansas. While construction and maintenance operations are under way, the two-lane highway will be reduced to a one-lane two-way work zone that requires temporary traffic control signs, flaggers, and a pilot car to coordinate vehicles entering and leaving the work zone. Four work zones were selected for field experiments. The traffic volumes of the selected work zones were moderate so that free-flow vehicle speeds were able to be collected in the upstream of the work zones.

2.3 RESEARCH METHODOLOGY

The objectives of this research were achieved using a five-step approach. These steps were 1) literature review, 2) field experiments and surveys, 3) experimental and survey data analyses, 4) comparison of trucks and passenger cars speed reductions, and 5) conclusions and recommendations.

1: Literature Review

The literature review was conducted to establish the background for this research. The topics of review included work zone crash characteristics studies, work zone traffic control methods, statistical methods in work zone safety analyses, and work zone safety research and development trends.

2: Field Experiments and Survey

The field experiments and survey include three phases; all of them were conducted in one-lane two-way rural highway work zones in Kansas.

Field Experiment Phase I: The main purpose of the experiment Phase I was to determine the effectiveness of a PCMS on reducing the speeds of passenger cars and trucks under three conditions: PCMS on, PCMS off (visible), and PCMS absent. In the experiment Phase I, two speed detector sensors, SmartSensor HD (Model 125), were used to measure vehicles' speed change before and after the PCMS. The PCMS used in the experiments was placed 750 ft upstream of the first temporary traffic control sign (W20-1: ROAD WORK AHEAD). One of the two speed detector sensors was placed 300 ft before the PCMS and another sensor was installed 200 ft after the PCMS so that the vehicle speed changes could be measured.

Field Experiment Phase II: In field experiment Phase II, seven speed sensors (TRAX Apollyon) were used so that enough speed data points could be collected to develop vehicle speed models in the upstream of work zones. With the speed profile models and measured mean speeds, the optimal deployment location of the PCMS could be determined.

Field Experiment Phase III: In field experiment Phase III, the optimal deployment location of the PCMS was validated when placing the PCMS within the range of the optimal deployment location. In addition, a survey on the impact of the PCMS on drivers' behavior in one-lane two-way rural highway work zones was conducted. The results of the survey provided in-depth understanding of drivers' opinions on the effectiveness of a PCMS in the upstream of the work zones.

3: Experimental and Survey Data Analyses

Experimental and survey data were analyzed using the SPSS software to determine the effectiveness of PCMS in one-lane two-way work zones. Various statistical analysis methods, including frequency analysis, hypothesis test, and regression techniques, were utilized throughout the data analysis period. Through the data analyses, the effectiveness of the PCMS on reducing vehicle speeds, vehicle speed profile models, and the optimal deployment location of the PCMS were determined.

4: Comparison of Truck and Passenger Car Speed Reductions

In this step, the speed reductions of trucks and passenger cars were compared. The truck-related crashes in highway work zones result a much higher severity than other types of work zone crashes. By analyzing the speed reductions of trucks and passenger cars, the difference of driving patterns between truck and passenger car drivers could be determined, and thus, countermeasures could be developed to mitigate the risks of truck-related crashes in the work zones.

5: Conclusions and Recommendations

Conclusions were made based on the results of data analyses. Recommendations on the improvements of one-lane two-way work zone safety were presented at the end as well as the needs for future research.

CHAPTER 3: LITERATURE REVIEW

3.1 INTRODUCTION

The MUTCD defines a highway work zone as an area of highway with construction, maintenance, or utility work activities (FHWA 2009c). A highway work zone can be divided into four areas as shown in Figure 3.1: “the advance warning area, the transition area, the activity area and the termination area” (FHWA 2009c). “The advance warning area is the section of a highway where road users are informed about the upcoming work zone”. “The transition area is the section of a highway where road users are directed out of their normal path”, usually involving strategic use of tapers. “The activity area is the section of a highway where the work activities take place. It is composed of the work space, the traffic space, and the buffer space”. “The termination area is the section of a highway following the activity area where the road users return to their normal path” (FHWA 2009c).

The existence of a highway work zone disturbs regular traffic flow, causes traffic delay and congestion, and thus, creates safety problems. Resurfacing, reconstruction, relocation, restoration, and rehabilitation are the main activities in work zones. These activities and the original highway transportation functions are often in conflict. Since 1960s, highway work zone safety has become a research focus and many researchers have published their findings on this subject.

In this chapter, the results of a comprehensive literature review on work zone safety are presented. The findings are organized in five categories including 1) previous analyses of vehicle crashes in work zones, 2) work zone traffic control methods, 3) the

Portable Changeable Message Sign (PCMS) application in highway work zones, 4) statistical methods used in work zone crash analysis, and 5) research and development trends in work zone safety.

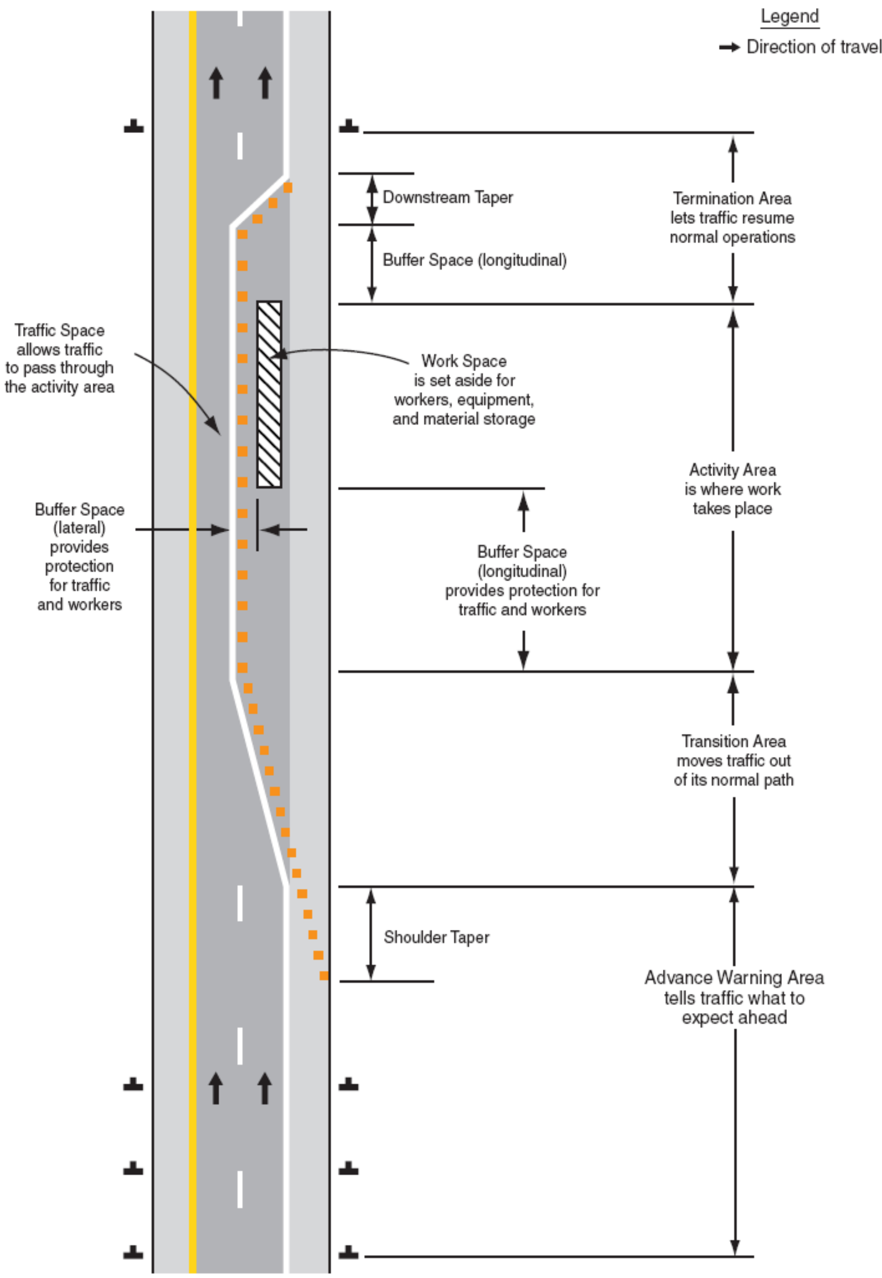


Figure 3.1 Component parts of a temporary traffic control zone, MUTCD (2003 Edition, Page 6C-3)

3.2 PREVIOUS ANALYSES OF VEHICLE CRASHES IN WORK ZONES

3.2.1 Characteristics of Work Zone Crashes

The review of the literature on the characteristics of work zone crashes shows that most of these studies were conducted statewide, and a few addressed nationwide work zone safety issues. The diverse data scopes produced inconsistent findings even in the same area. The studies reviewed are categorized into the following areas:

Crash rates

Crash severity

Crash location

Crash type

Other crash characteristics

3.2.1.1 Crash Rates

Work zones on highways undoubtedly disturb the traffic flow, result in a decrease of capacity, and create hazardous environments for motorists and workers. Table 3.1 lists the studies of work zone crashes rates after the late 1970s. It can be concluded that work zone traffic safety is a problem nationwide because of the increased rates.

Table 3.1 Previous Crash Rates Studies

No.	Year	Study Data	Location	Researchers	Crash Rate
1	1978	151 accidents	Ohio	Nemeth and Migletz	Increase
2	1978	79 projects	Multi States	Graham et al.	6.9 percent increase
3	1988	Crashes in Chicago Area Expressway System	Illinois	Rouphail et al.	Increase[1]
4	1989	Total 499 crashes occurred in 114 projects	New Mexico	Hall and Lorenz	26 percent increase
5	1990	7 projects	Virginia	Garber and Woo	57 percent[2] 168 percent[3] increase
6	1990	2,013 accidents From 1983-1986	Kentucky	Pigman and Agent	Increase
7	1996	25 projects	Indiana	Pal and Sinha	Increase
8	2002	36 projects	California	Khattak	21.5 percent increase

[1]: Urban Freeway
[2]: Multilane Highway
[3]: Two-lane Highway

Nemeth and Migletz studied 151 accidents in Ohio; the researchers compared the accident rate per million vehicle kilometers or per million vehicle miles before, during, and after construction and maintenance operations. The results showed that crash rates during construction increased significantly (Nemeth and Migletz 1978). Graham et al. analyzed 79 projects in seven states. As a whole, crashes increased 6.8 percent. The change of crash rate was found to vary substantially among individual projects (Graham et al. 1978). Rouphail et al. selected 46 sites in the Chicago Area Expressway System and collected the crash data from 1980 to 1985. The researchers found that the crash frequency increased by 88 percent during the existence of the work zone site (Rouphail et al. 1988). Hall and Lorenz in New Mexico found that crashes during construction increased 26 percent compared with crash rate in the previous years when no construction occurred (Hall and Lorenz 1989). In 1990, Garber and Woo selected 7 project sites in Virginia; the researchers found that, “accident rates at work zones on multilane highways in Virginia increase on the average by about 57 percent" and "by about 168 percent on two-lane urban highways when compared with accident rates just prior to the installation of the work zones" (Garber and Woo 1990). Pigman and Agent examined the accident reports from 1983 to 1986 which contained 2,013 accidents in Kentucky. The researchers discovered that "at 14 of the 19 locations where accident rates were calculated, rate during construction exceeded those in the before period" (Pigman and Agent 1990). Pal and Sinha found that there was a significant change of accident rates between before and during construction in Indiana (Pal and Sinha 1996). Khattak et al. pointed out the rate of total work zone crashes was 21.5 percent higher than the pre-work zone crash rate and indicated that "work zone projects on limited-access roadways can be more hazardous than those same segments in the pre-work zone period" (Khattak et al. 2002). These studies demonstrated that the increase in crash rates as a result of construction and maintenance "was highly variable and likely dependent upon specific factors related to traffic conditions, geometrics, and environment" (Wang et al. 1996).

3.2.1.2 Crash Severity

Table 3.2 lists the previous studies on the crash severity in work zones. Inconsistent conclusions have been reached about whether more severe crashes occur in work zones.

Table 3.2 Previous Crash Severity Studies

No.	Year	Study Data	Location	Researchers	Crash Severity
1	1978	151 accidents	Ohio	Nemeth and Migletz	Increase
2	1981	WZ accidents in 1977	Texas	Richards and Faulkner	Truck-related crash severity increase
3	1981	2127 accidents	Virginia	Hargroves	Less severe
4	1987	FARS & National Survey	Multistate	AASHTO	Increase
5	1988	Crashes in Chicago	Illinois	Rouphail et al.	Less severe
6	1989	Total 499 crashes occurred in these 114 projects	New Mexico	Hall and Lorenz	No significant difference
7	1990	2,013 accidents From 1983-1986	Kentucky	Pigman and Agent	Increase
8	1990	7 projects	Virginia	Garber and Woo	No significant difference
9	1995	1982-1986 accidents	Ohio	Ha and Nemeth	Less severe Truck-related crash severity increase
10	1995	Crashes in three states	Multistate	Wang et al.	Less severe
11	2000	181 crashes	Georgia	Daniel et al.	Truck-related crash severity increase
12	2002	1484 crashes	Virginia	Garber and Zhao	Increase
13	2004	77 fatal crashes	Texas	Schrock et al.	Truck-related crash severity increase
14	2006	157 fatal crashes	Kansas	Li and Bai	Truck-related crash severity increase

Nemeth and Migletz showed that the severity of work zone crashes increased, especially for injury crashes (Nemeth and Migletz 1978). A national study discovered that the fatal accident frequency and the fatalities per accident on average were higher in work zones nationwide (AASHTO 1987). Pigman and Agent (1990) concluded that work zone crashes were more severe than other crashes. Garber and Zhao collected 1,484 crashes from 1996 to 1999 in Virginia and pointed out that more severe crashes happened in work zones (Garber and Zhao 2002). However, Hall and Lorenz (1989) and Garber and Woo (1990) concluded the severity was not significantly different between work zone crashes and non work zone crashes. Hargroves (1981), and Ha and Nemeth (1995) found that work zone crashes were less or slightly more severe than other crashes. Work zone crashes involving large trucks were more severe than other crashes. Richards and Faulkner (1981), Pigman and Agent (1990), Ha and Nemeth (1995), Daniel et al. (2000), Schrock et al. (2004), and Li and Bai (2006) pointed out the disproportionate number of large trucks involved in severe crashes (fatal and injury).

3.2.1.3 Crash Location

Many researchers agreed that there is an unbalanced crash distribution along the work zones. When considering the different locations in the work zone, Pigman and Agent (1990) pointed out that the most severe crashes occurred in the advance warning area. Nemeth and Migletz (1978) and Hargroves (1981) indicated that the activity area was the area which could be susceptible to work zone crashes. Rural highways account for more work zone crashes compared with urban highways; a national study found that about 68 percent of all fatal crashes occurred on rural highways (AASHTO 1987). Pigman and Agent (1990) discovered that the percentage of work zone crashes occurring in rural areas was much higher than in business and residential areas. Daniel et al. (2000) concluded the fatal crash rate in rural work zones increased about 13 percent when work zones were on the road. A study conducted by Li and Bai found that 63 percent of fatal crashes happened on two-lane highways in Kansas (Li and Bai 2006).

3.2.1.4 Crash Type

The prevailing types of work zone crashes varies with times and locations in the work zones (Li and Bai 2006). However, results of most of the previous studies indicated that the rear-end collision was one of the most frequent work zone crash types (Nemeth and Migletz 1978; Hargroves 1981; Rouphail et al. 1988; Hall and Lorenz 1989; Pigman and Agent 1990; Garber and Woo 1990; Wang et al. 1995; Ha and Nemeth 1995; Sorock et al. 1996; Daniel et al. 2000; Mohan and Gautam 2002; Garber and Zhao 2002; Chambless et al. 2002; Bai and Li 2006; Bai and Li 2007; and Li and Bai 2008). Other major types of work zone crashes include same-direction sideswipe collision (Nemeth and Migletz 1978; Pigman and Agent 1990; Garber and Woo 1990; and Li and Bai 2008), angle collision (Pigman and Agent 1990), and hit-fixed-object crashes (Nemeth and Migletz 1978; Hargroves 1981; Mohan and Gautam 2002; and Garber and Zhao 2002).

3.2.1.5 Fatal Crash Characteristics

The study of fatal crashes allowed for an evaluation of the most severe type of crashes and indicated where safety improvements should be focused. Janice Daniel and other researchers studied fatal crashes in Georgia, which included 181 crashes from 1995 to 1997. Daniel pointed out fatal crashes in work zones were more likely to be involved with another vehicle than non work-zone fatal crashes, and trucks were involved in a higher proportion (20 percent) of fatal crashes compared with non work-zone fatal crashes (13 percent). Rear-end crashes represented a high proportion (12.1 percent) of fatal crashes in work zones compared with those in non work-zone locations (5.0 percent) (Daniel et al. 2000). In addition, 28 percent of fatal crashes in work zones occurred on rural principal roadways compared with 15 percent of fatal crashes in non-work-zone locations.

Schrock et al. (2004) collected data from 77 fatal crashes in work zones in Texas from February 2003 to April 2004. The researchers found that 29 percent of all fatal crashes involved a large truck, typically with a truck striking another vehicle or vehicles. In addition, the researchers pointed out one trend in the data that large truck-involved crashes were more likely to involve more than two vehicles. This seems reasonable because the energy that a large truck had would make it more likely to hit multiple vehicles before it stopped. Researchers concluded that 8 percent of investigated fatal crashes had a direct influence from the work zone, and 39 percent of the investigated crashes had an indirect influence from the work zone (Schrock et al. 2004).

After analyzing 157 fatal crashes in Kansas, Li and Bai (2006) found that head-on collision was the dominant type in fatal crashes; a large percentage of fatal crashes involved trucks (40 percent); and almost all of these crashes were multi-vehicle crashes. Their study results implied that truck involvement could increase the severity of work zone crashes. In addition, 63 percent of fatal crashes in work zones in Kansas occurred on two-lane highways (Li and Bai 2006).

Based on the results of previous fatal crash studies in work zones, two common characteristics are summarized as follows:

1. Crashes involved trucks were more severe in work zones than those in non-work-zones.
2. A high percent of fatal crashes occurred on rural highway work zones.

3.2.1.6 Other Crash Characteristics

Most studies concluded that human errors, such as excess speeds, following too close, misjudging, and inattention, were the most common causes for work zone crashes (Nemeth and Migletz 1978; Hargroves 1981; Hall and Lorenz 1989; Pigman and Agent 1990; Garber and Woo 1990; Ha and Nemeth 1995; Chambless et al. 2002; and Li and Bai 2008). Two studies (Hall and Lorenz 1989; and Garber and Woo 1990) indicated that multi-vehicle crashes were overrepresented, whereas nine studies (Nemeth and Migletz

1978; Hargroves 1981; Richards and Faulkner 1981; Hall and Lorenz 1989; Pigman and Agent 1990; Ha and Nemeth 1995; Daniel et al. 2000; Schrock et al. 2004; and Li and Bai 2006) indicated that truck-related crashes were overrepresented.

Pigman and Agent (1990) found that “crashes during darkness were more severe”, Nemeth and Migletz (1978) found that “the proportion of tractor-trailer and bus-caused accidents at night and dawn or dusk was greater than the proportion for other vehicles.” Richards and Faulkner (1981) concluded that “nighttime crashes were especially concentrated at the transition area.” Ha and Nemeth (1995) also found that “night crashes were more likely to be the fixed-object crashes and single-vehicle crashes were predominant at night.”

3.2.2 Truck-related Crashes in Work Zones

Truck related crashes contribute to a significant percentage of motor vehicle crashes in the United States, which often result in fatalities and injuries (Bezwada and Dissanayake 2009). The information from the Fatality Analysis Reporting System (FARS) shows that there were 50,430 fatal crashes in 2008, 8.1% (4,066) of them were large truck related, 37.8% (19,072) were light truck related. Here a light truck is referred to as a truck of 10,000 pounds gross vehicle weight or less; a large truck is over 10,000 pounds gross vehicle weight (FARS 2008).

Because of the characteristics of trucks, it is difficult for truck drivers to maneuver large trucks smoothly on roadways. Trucks have a slower initial speed and a longer deceleration time. Truck drivers face many challenges when traversing on Interstate or state highways, at intersections, or taking turns (Bezwada and Dissanayake

2009). Figure 3.2 shows the truck driver's blind spots, which make it more challenging for truck drivers to avoid hitting other vehicles.

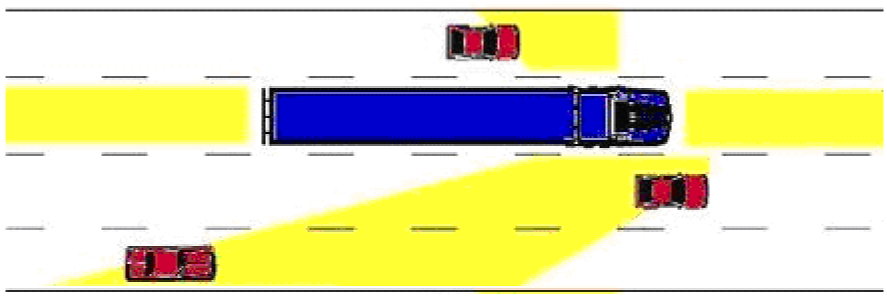


Figure 3.2 Blind spots around a large truck (American trucking associations website)

The amount of truck miles traveled is dramatically increasing with the growing rate of freight movement, which in turn requires attention to the safety of truck transportation. Bezwada and Dissanayake (2009) found that the initial collision point on a truck is the "front side." This finding weakens the argument that the poor visibility of trucks on their rear side leads to the majority of rear-end truck crashes. In fact, angle crashes are the highest proportion in truck-related collision at about 34.2%. There were 73.7% of all vehicles disabled in fatal truck-related crashes on rural roadway compared to 61.0% vehicles disabled on urban roadways (Bezwada and Dissanayake 2009).

Benekohal et al. (1995) conducted a statewide opinion survey of 930 semitrailer drivers in Illinois in 1993. Researchers found that about 90 percent of truck drivers consider traveling through work zones to be more hazardous than non work zone areas. About half of the drivers wanted to see an advance warning sign 5 to 8 kilometers (3 to 5 mi) ahead of the work zone. The drivers did not have a clear preference between one-lane closure and median crossover configurations. About two-thirds of drivers considered the speed limit of 89 km/hr (55 mi/hr) about right, but one-fourth of them believed it was too fast. Nearly half of drivers would exceed a speed limit of 72 km/hr (45 mi/hr), and nearly one-fifth of them would drive at least 8 km/hr (5 mi/hr) faster than the speed limit. About one-third of drivers said the flaggers were hard to see, and about half of them considered that directions given by flaggers were confusing sometimes or most of the time. About three-fourth of the drivers indicated that the arrow boards were too bright. For most of the drivers, work zones signs were clear and not confusing, but 14 percent disagreed. About one-fifth of the drivers said some signs should be added to the work zones. About one-third of the crashes were in the advance warning area, and about two-third of crashes were in the transition area.

In another paper, Benekohal and Shim pointed out that, in terms of vehicle miles traveled (VMT), fatal crash rates for large trucks had been consistently higher than the rates for passenger cars; semitrailer trucks were underrepresented in the Property Damage Only (PDO) and injury crashes, but overrepresented in fatal crashes (Benekohal and Shim 1999).

Meyers compared truck and passenger-car crash rates from 1976 to 1978 at 34 limited-access facilities (21 toll expressways and turnpikes, and 13 bridges and tunnels). He found that fatal, injury, and overall expressway crash rates for heavy trucks exceeded that of passenger cars (Meyers 1981). Garber and Joshua found that 75% of all large-truck crashes and 91% of large-truck fatal crashes were attributed to driver-related errors (Garber and Joshua 1990). Hall and Lorenz found that in New Mexico the number and rate of truck-related crashes increased during the construction season (Hall and Lorenz. 1989). Work zone crashes involve large trucks are more severe than other crashes, Daniel et al. (2000); Schrock et al. (2004); Li and Bai (2006); Ha and Nemeth (1995); Pigman and Agent (1990); and Richard and Faulkner (1981) pointed out the disproportionate number of large trucks involved in severe crashes (fatal and injury).

3.2.3 Cost of Work Zone Crashes and Highway Capacity Loss

Sorock et al. (1996) studied 3,686 crashes from Liberty Mutual Insurance Company's automobile liability and physical damage claims which occurred from 1990 through 1993. The researchers found that the most common crash type was the rear-end collision (31 percent) followed by the hit-small-object collision (11 percent). Most crashes occurred when the vehicle was stopping or slowing (26 percent). The average direct cost of the 3,686 motor vehicle crashes in highway work zones was calculated at $3,687 per crash; the median cost was $687; and the range was from $0 to $2,250,698 (Sorock et al. 1996).

Mohan and Gautam (2002) continued the cost study of work zone crashes based on Sorock's work. In 1996, about 3.71 million dollars per fatality and $75,487 per injury were determined based on the 1996 cost. From 1996 to 1998, the average cost of work zone crashes was $6.18 billion per year in the United States.

Ullman et al. (2004) collected data in five regions across the country in 2001, which included the Phoenix and Prescott districts, Arizona; Delaware district, Ohio; Bryan district, Texas; Richmond district, Virginia; Olympia and Northwest regions, Washington. Based on the data from these five regions, the researchers made estimations on national work zone exposure measures during the 2001 calendar year. It was estimated that "annually 26.5 percent of the National Highway System (NHS), or approximately 43,500 route miles, experienced at least 1 day of work activity during 2001;" " the average length of a work zone contract was estimated to be 5.0 miles, while the area of actual work activity within that project was estimated to be only 1.5 miles each day." On a particular day of July 25, 2001, which was estimated to be the date of peak work activity on the NHS, "approximately 7,900 route miles, or 4.8 percent of the NHS experienced some type of work activity. In the meantime, another 5,100 route miles, or 3.1 percent of the NHS, appeared to have a work zone that was inactive." "Lane and shoulder closures accounted for a capacity loss of 41 million vehicles per day and represented the equivalent loss of 4,370 lane miles over the duration of a typical work shift on a typical work day. This daily loss in capacity equates to a capacity loss of over 8.1 billion vehicles on the NHS during the entire calendar year." "Approximately 1 percent of the Vehicle Miles Traveled (VMT) on the NHS, or 12 billion vehicle miles, passed an active work zone in 2001," and "nearly 5 percent of the VMT on the NHS, or 61 billion vehicle miles, passed an inactive work zone" (Ullman et al. 2004).

3.2.4 Summary of Work Zone Crash Characteristics

The characteristics of the work zone crashes studied in the previous research projects are summarized as follows:

1. It has been a long time since researchers paid attention to the safety of work zones in the United States. In the previous forty years, most work zone crashes studies were conducted statewide, and the findings on this topic varied in some aspects.

2. Many studies agreed that the appearance of work zones on the highway had increased the rate of crashes compared with non-work zones. Some studies showed higher crashes rates were found in rural highway work zones.

3. There is no consistent conclusion on the severity of work zone crashes. However, truck-involved crashes in work zones were more severe than those in non-work-zones.

4. Most researchers agreed on unbalanced crash distribution within the work zones. No consistent conclusions have been reached on the most dangerous areas in the work zones.

5. The rear-end crash was the most frequent crash type in work zone crashes. Same-direction sideswipes collisions, angle collisions and head-on collisions were also frequently found among fatal work zone crashes.

6. Most work zone crashes occurred in the daytime. There was no significant difference between severe weather and normal weather conditions for work zone crashes. Work zone crashes during nighttime were more severe than both daytime work zone crashes and non work zone crashes.

7. Human errors, such as excess speed and inattention driving, were the major causes of work zone crashes.

3.3 WORK ZONE TRAFFIC CONTROL METHODS

Work zone traffic control has become increasingly complex as the emphasis of highway programs has shifted from new construction to rehabilitating and improving existing roads. Work zone projects require numerous traffic control devices (TCDs) and other safety features on or adjacent to travel lanes. The 2009 version of MUTCD and its periodic revisions represent the result of many years of experimentations and are the national engineering standards for highway traffic controls, including traffic controls in work zones. Despite the progress has made so far, safety remains a challenge issue in work zones and there is still room for further improvements in traffic controls.

Traffic crashes in highway work zones are caused by a combination of factors, which include “driver error, inadequate visibility, poor road surface conditions, construction obstructions, inadequate traffic control and information, and improper management of material, equipment, and personnel in work zones” (Linda et al 2002). Among these factors, driver error, such as excessive speed for existing conditions, is a leading causal factor of crashes (Li and Bai 2009). To provide continuity of reasonably safe and efficient traffic flow during road works, temporary traffic control (TTC) devices are employed in work zones. According to the MUTCD, TTC devices that are commonly used in work zones include flaggers, traffic signs, arrow panels, channelizing devices, pavement markings, lighting devices, temporary traffic control signals, rumble strips, and portable changeable message signs (FHWA 2009c). The rest of this section presents some of the traffic control methods utilized in the work zone, including the use of law enforcement, flagging, rumble strips, and speed monitoring display. The main purpose of using these methods is to reduce and/or control vehicle speeds in work zones.

3.3.1 Law Enforcement

It is generally agreed that one of the most effective ways of reducing vehicles’ speed in a work zone is to have a police car positioned at the beginning of the work zone with its lights flashing and radar on (Arnold 2003). Based on the literature review, a number of previous studies, shown in Table 3.3, support this statement.

Table 3.3 Previous Law Enforcement Studies

No.	Year	Research Subject	Researchers	Location
1	1985	Field Evaluation of Work Zone Speed Control Techniques	Richards, S.H., Wunderlich, R.C. and C.L. Dudek	Texas
2	1988	Speed Control through Freeway Work Zones: Techniques Evaluation	Errol C. Noel, Conrad L. Dudek, Olga J. Pendleton and Ziad A. Sabra	Delaware
3	1992	Effects of Police Presence on Speed in a Highway Work Zone	Benekohal, R.F., and Resende, P.T.V, and Orloski, R.L.	Illinois
4	1993	Work Zone Safety Device Evaluation	McCoy, P.T. and Bonneson, J.A.	South Dakota
5	1999	Effectiveness of Law Enforcement in Reducing Vehicle Speeds in Work Zones	Minnesota Department of Transportation	Minnesota
6	2001	Construction Work Zone Safety	Christopher R. Huebschman, Camilio Garcia, Darcy M. Bullock, Dulcy M. Abraham	Indiana
7	2003	Use of Police in Work Zones on Highways in Virginia	Arnold, E.D.	Virginia
8	2008	Effectiveness of Speed Control Measures on Nighttime Construction and Maintenance Projects: Some New Evidence	Lindsay Miller, Dulcy Abraham and Fred Mannering	Indiana

In 1985, Richards et al. conducted field studies in Texas to evaluate selected methods of slowing vehicle speeds to an acceptable level. It was concluded by using field experiments that the use of law enforcement was effective in slowing traffic on two-lane two-way highways. A stationary patrol car reduced average speeds by 4 to 12 mph (6 to 22 percent speed reduction) and a circulating patrol car reduced speeds by 2 to 3 mph (3 to 5 percent speed reduction) (Richards et al. 1985).

Noel et al. (1988) selected eight study sites on Interstate 495 in the suburbs of Wilmington, Delaware. The results of field studies indicated that police radar and police controller were effective in reducing vehicle speeds in both the short term (about 3 days) and the long term (more than 10 days) after the speed control treatments (police radar and controller) were implemented on the selected freeway work zones. “The law enforcement method demonstrated a strong long term speed reduction capability” (Noel et al. 1988).

Benekohal et al. (1992) examined the impact of the presence, and then the absence, of marked police cars on vehicle speeds at rural interstate work zones in Illinois. The average speeds of cars and trucks were reduced by about 4 and 5 mph, respectively, while a police car was circulating through the work zones. "The numbers of cars and trucks exceeding the speed limit through the work zones were reduced by 14 and 32 percent, respectively" (Benekohal et al. 1992).

In South Dakota, McCoy and Bonneson conducted a research project to identify and evaluate traffic control devices to improve the safety of traffic operations in work zones. The researchers found that a stationary police car with an officer inside, its lights flashing, and its radar active reduced the average free-flow speed of vehicles from 25 to 30 mph (McCoy and Bonneson 1993).

Engineers from the Minnesota Department of Transportation measured the effectiveness of positioning a patrol car with its activate lights and flasher, the patrol car parked approximately 500 to 600 ft in the upstream of work zones on a rural interstate, an urban freeway, and a metro location. "The 85th percentile speeds at the rural interstate location were reduced from 51 to 42 mph; the 85th percentile speed was decreased from 66 to 58 mph on the urban freeway where the posted speed limit remained the same at 55 mph. At the metro location, where posted speeds were reduced from 50 (before work zone) to 40 mph, the 85th percentile speed was reduced from 58 to 47 mph" (MDOT 1999).

In 2001, Huebschman et al. evaluated several traffic management technologies in Indiana. The researchers found that the presence of law enforcement significantly reduced speeds by greater than 5 mph at the location adjacent to the trooper (Huebschman et al. 2003).

Arnold conducted a research project to determine the effectiveness of police presence on reducing vehicles' speeds though a survey. The results of the survey proved that the presence of police was effective on reducing vehicles' speeds in work zones in Virginia (Arnold 2003). Miler et al. (2008) indicated that the use of law enforcement reduced speeds about 5.3 mph for vehicle in work zones in Indiana.

From the literature review above, it is clear that the use of the law enforcement is effective on reducing vehicles' speeds. Motorists tend to slow down with the presence of police. Although this method is an effective measure on reducing speeds in work zones, it is limited in use because of its cost. The cost for a police officer, including benefits and 2 percent portion of supervisor's time, were estimated at $38.75 per hour in 1998 (Bloch 1998).

3.3.2 Flagging

Flaggers are qualified personnel uniformed with high-visibility safety apparel and equipped with hand-signaling devices, such as STOP/SLOW paddles, lights, and red flags to control road users through work zones. "Flaggers should be stationed at a location so that the road users have sufficient distance to stop at an intended stopping point, and should be preceded by an advance warning sign or signs and be illuminated at night" (FHWA 2009c).

Richards et al. (1985) found that using the flagging method did contribute to a 3 to 12 mph speed reduction for vehicles approaching work zones. Flagging is most effective on rural two-lane highways. McCoy and Bonneson (1993) found that innovative flagging procedures were effective in reducing the speed of vehicle approaching a work zone with a range from 9.2 mph to 15.2 mph. Two innovative flagging procedures in this research project were that in one of the procedures, the flagger wore a conventional orange vest and used an orange sign paddle, whereas in another procedure, the flagger wore yellow-green overalls and used a green background yellow legend sign paddle. The flagger in both procedures used the flagging signal in the MUTCD except that, instead of holding a STOP/SLOW sign paddle, the flagger held a 45 MPH sign paddle in one hand and motioned for traffic to slow down with the other hand (McCoy and Bonneson 1993). Jones and Cottrell (1999) indicated that the proposed sign, a STOP/SLOW paddle for the most part was understood by Virginia drivers and appeared to be effective at conveying its message.

3.3.3 Rumble Strips

Rumble strips provide an auditory and vibratory warning to drivers about upcoming work zones. Meyer (2000) studied the effectiveness of removable rumble strips on reducing vehicle's speed in work zones in Kansas. This study showed that the mean speeds decreased between 0 and 3.2 km/h (2 mph) when the rumble strips were installed. The minor reduction was probably due to the fact that rumble strips were spaced too close together and were not thick enough to create significant speed reductions (Meyer 2000). Fontaine and Carlson (2001) found that the portable rumble strips generally did not have a significant impact on reducing average speeds of passenger cars but had a greater impact on reducing mean speeds of trucks. McCoy and Bonneson (1993) found that rumble strips actually resulted in a small increase in average speed. The mixed results on the effectiveness of rumble strips indicate that there is a need to continue conducting the research on this subject.

3.3.4 Speed Monitoring Display

The speed monitoring display (SMD) is a traffic control device that uses radar to measure the speeds of approaching vehicles and shows these speeds to drivers on a digital display panel. Since 1970s, it has been successfully applied both in the United States and abroad. This device was applied to slow traffic down by displaying and catching drivers aware of the speeds they are traveling. Previous studies, shown in Table 3.4, consistently indicated that vehicle speeds were reduced by using the SMD in work zones.

Table 3.4 Previous Monitoring Displays with Radar Studies

No.	Year	Research Subject	Researchers	Location
1	1995	Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways	Patrick T. McCoy, James A. Bonneson, and James A. Kollbaum	South Dakota
2	1998	Comparative Study of Speed Reduction Effects of Photo-Radar and Speed Display Boards	Steven A. Bloch	California
3	2001	Evaluation of Speed Displays and Rumble Strips at Rural-Maintenance Work Zones	Michael D. Fontaine and Paul J. Carlson	Texas
4	2001	Long-Term Effectiveness of Speed Monitoring Displays in Work Zones on Rural Interstate Highways	Geza Pesti and Patrick T. McCoy	Nebraska
5	2006	Improving Compliance with Work Zone Speed Limits – Effectiveness of Selected Devices	Marcus A. Brewer, Geza Pesti, William Schneider IV	Texas

McCoy et al. indicated that speed monitoring displays with radar were effective in reducing the speed of vehicles approaching the work zones. The mean speeds were about 6 to 8 km/hr (4 to 5 mi/hr) lower after the speed monitoring displays were installed (McCoy et al. 1995). Bloch (1998) found that both photo-radar and speed display boards offer better overall results on reducing vehicle speeds. The devices appeared particularly effective at reducing the speeds of vehicles traveling 16 km/h (10 mph) or more over the speed limit (Bloch 1998). Fontaine and Carlson (2001) pointed out mean speeds of vehicles were reduced up to 10 mph when the speed display was present. Pesti and McCoy (2001) found that the SMDs were effective in lowering speeds and increasing the uniformity of speeds over a period of 5 weeks in rural interstate highway work zones. Brewer et al. (2006) indicated that devices with the ability to display drivers' speeds have considerable potential for reducing speeds and improving compliance.

3.4 PORTABLE CHANGEABLE MESSAGE SIGN

A Portable Changeable Message Sign (PCMS), sometimes referred to as a Changeable Message Sign (CMS), a Variable Message sign (VMS) or a Dynamic Message Sign (DMS), is the traffic control device that can display a variety of messages to inform motorists of driving conditions. "This capability is achieved through elements on the face of the sign that can be activated to form letters or symbols. A PCMS can capture motorists' attention, relay information that is difficult to accomplish with static signing, and can be used to supplement other required signing". In addition, "a PCMS can be an effective temporary traffic control device when used appropriately in work zones" (FHWA 2003); however, its effectiveness can be diminished if the device is overused.

Several research projects, shown in Table 3.5, were conducted to study the effectiveness of a PCMS. Richards et al. (1985) found that with the CMS treatment, the range of speed reduction was 3 mph to 9 mph, about 2 percent to 9 percent reduction. Benekohal and Shu (1992) indicated that though speed reductions were statistically significant, in general, the effectiveness of CMS was not practically significant for truck-speed reduction (1.4 mph). When placing a CMS in the activity area, it was effective in reducing the average speed of cars by 1.7 mph at a point near the CMS. When placing two CMS devices in the activity area, the reduction ranged from 2.6 to 4.7 mph for cars and trucks (Benekohal and Shu 1992).

Table 3.5 Previous Portable Changeable Message Sign Studies

No.	Year	Research Subject	Researchers	Location
1	1985	Field Evaluation of Work Zone Speed Control Techniques	Stephen H. Richards, Robert C. Wunderlich and Conrad L. Dudek	Texas
2	1992	Speed Reduction Effects of Changeable Message Signs in a Construction Zone	R. F. Benekohal and Jie Shu	Illinois
3	1995	Control of Vehicle Speeds in Temporary Traffic Control Zones (Work Zones) Using Changeable Message Signs with Radar	Nicholas J. Garber and Surbhi T. Patel.	Virginia
4	1998	Influence of Exposure Duration on the Effectiveness of Changeable-Message Signs in Controlling Vehicle Speeds at Work Zones	Nicholas J. Garber and Srivatsan Srinivasan	Virginia
5	1999	Changeable Message Sign Messages for Work Zones	Conrad L. Dudek	New Jersey
6	2003	Construction Work Zone Safety	Christopher R. Huebschman, Camilio Garcia, Darcy M. Bullock, Dulcy M. Abraham	Indiana
7	2003	Evaluating Speed-Reduction Strategies for Highway Work Zones	Chunyan Wang, Karen K. Dixon, and David Jared	Georgina
8	2007	Driver Understanding of Sequential Portable Changeable Message Signs in Work Zones	Brook R. Ullman, Gerald L. Ullman, Conrad L. Dudek, and Alicia A. Williams	Laboratory Texas
9	2008	Evaluation of Messages on Changeable Message Signs as a Speed Control Measure in Highway Work Zones	Wesley C. Zech, Satish B. Mohan, Jacek Dmochoqawski	New York

Garber and Patel (1995) pointed out that messages of “HIGH SPEED SLOW DOWN” and “YOU ARE SPEEDING SLOW DOWN” appeared to have a greater impact on vehicle speeds than other messages. Besides the reduction of vehicle speeds, a CMS was an effective means of reducing speed variance, which is also considered to be critical factor to improve the safety of a work zone. In addition, the CMS was effective in short-term work zones, up to one week at a time (Garber and Patel 1995). Three years later, Garber and Srinivasan (1998) found that the CMS with radar was effective for long-term work zones; the amount of speed reduction increased over the long term. There was no significant difference in the speed reduction for each vehicle class over the different weeks; the CMS with radar reduced the probability of speeding at work zones and this effect was true for all exposure durations (Garber and Srinivasan 1998).

When it came to displays on the CMS, Dudek pointed out that “a dash might be substituted for the word Thru; the term Weekend was not a good descriptor for roadwork that begins on Friday evening or ends on Monday morning; the term Days did not connote specific daytime, off-peak times for roadwork; the term Nites is an acceptable substitute for Nights” (Dudek 1999).

Huebschman et al. (2003) found that it was not clear these signs would reduce fatal crashes resulting from approaching the work zone traffic queue at prevalent speeds. Wang et al. (2003) found that a Changeable Message Sign with Radar (CMR) provided significant speed reductions (7 to 8 mph) for approaching traffic at locations immediately adjacent to the CMR. Ullman et al. (2007) found that the use of sequential PCMSs will result in comprehension rates comparable with those obtained by presenting the same information on a large, single-phase DMS. Ullman also strongly indicated the need to keep the overall message below the four-unit maximum recommended in existing guidelines (Ullman et al. 2007). Zech et al. (2008) pointed out that “WORK ZONE/MAXSPEED/ 45MPH~BE/PREPARED/TO STOP” was very effective in reducing vehicle speeds by 3.3-6.4 mph in driving lane and 3.7-6.7 mph in the passing lane. This message, however, increased the speed standard deviation from approximately 1 to 2 mph.

3.5 STATISTICAL METHODS USED IN WORK ZONE SAFETY ANALYSES

Many statistical approaches were used to analyze the effectiveness of certain methods or devices on improving work zone safety. The objective of this review is to establish a background of the currently available statistical methodologies that could be utilized for work zone safety analyses.

The before-and-after study is a common method used in work zone study. For this kind of study, crash counts for several years (both before and after a treatment) are recorded for an affected section and a comparison section (Pal and Sinha 1996). Then, "any change in the crash rate on the affected section after the treatment is checked against the condition on the comparison section. If the crash rate is significantly different, then it is concluded that the treatment has been effective". "The test for comparability of the data described is conducted using the G^2 statistic; this statistic is based on the numbers of crashes that take place on a test section and an associated comparison section during periods of both the normal operating condition and the work zone condition" (Pal and Sinha 1996).

A before-and-after study can be used for different highways or highway entities, such as intersections, highway sections, railroad crossings, and among others. "The period of time considered before and after the improvement must be the same and must be long enough to allow the observation of changes in crash occurrence" (Elias and Herbsman 2000). The comparison usually is done by tests of statistical significance at certain levels of confidence. However, many researchers have criticized this method. First, many statisticians argued that "statistical methods should not be used to draw conclusions from observational studies". Another criticism is that this method can not be useful without “differentiating what portion of the changes in crash rate is truly due to the treatment and what portion is due to the change in contributing factors alone” (Elias and Herbsman 2000).

In field experiments, sufficient data are needed to ensure the accuracy of analysis. The minimum sample size can be determined for a desired degree of statistical accuracy by using the following equation (Robertson et al. 1994):

$$N = (S * \frac{K}{E})^2$$

Where

N = minimum number of measured data;

S = estimated sample standard deviation;

K = constant corresponding to desired confidence level; and

E = permitted error in the average data estimated.

In a study on the use of drone radar in South Carolina, Eckenrode et al. (2007) took 5.0 as the standard deviation. For a 95% confidence level, K equals 1.96 E, which reflected the precision of the observed speeds, and it is the maximum tolerance for errors in the data collection. In the study, a value of 1.0 mph was assumed for E. Thus, the minimum sample size at the 95%-confidence level is 96.

The measures of effectiveness (MOEs) used in the evaluation of the speed control devices include (1) mean speed, (2) 85th percentile speed, (3) standard deviation of speed, and (4) percentage of vehicles complying with the speed limit (Brewer et al. 2006). Traffic control devices are evaluated based on the differences between these MOEs for the period before and during the operation of the devices. MOEs are determined for each vehicle type (passenger cars and trucks) for each treatment option at all speed measurement points at the two sites. “Then the differences in MOEs between the periods with and without treatments are calculated and tested for statistical significance” (Brewer et al. 2006).

Analysis of Variance (ANOVA) and the t-test are used to test the equality of population means. ANOVA is the most common type of test in experimental result analysis. It is an effective analysis tool which compares populations simultaneous to determine if they are identical or different. ANOVA determines whether means of several treatments are equal or not by examining the population variances using the F Statistic. In addition to ANOVA, the univariate analysis of variance (UNIANOVA) is also used in comparison analysis. UNIANOVA is a two-way analysis of variance, which is useful when it is necessary to “compare the effect of multiple levels of two factors and to combine every level of one factor with every level of another factor”. It is also able to “estimate the effects of interaction between the two factors with multiple measurements at each level” (Weinberg and Abramowitz 2008).

The sampling distribution of independent observations from a normal distribution can be standardized to find z and compare it with z_c, which is determined by the α value. In a sample with unknown variance, the t distribution, also called Student’s t-distribution, is used with the best estimate of the mean, instead of using the normal distribution. The t distribution is primarily used for determining the statistically significant difference between two sample means and confidence intervals of the difference between two population means. When dealing with inferences about the means of matched pairs, the following equation is used to test the hypothesis for matched pairs (Triola 2004).

$$t = \frac{\bar{d} - \mu_d}{s_d / \sqrt{n}}$$

Where

Degrees of freedom = n-1

μ_d = mean value of the differences d for the population of all matched pairs;

$\bar{d}$ = mean value of the differences d for the paired sample data (equal to the mean of the x-y values);

s_d = standard deviation of the differences d for the paired sample data;

n = number of pairs of data.

The proportionality test can be used to determine the significance of distributions. “The proportionality test is a test of the quality of two independent means, namely p_1 and p_2, which are the probabilities of success resulting from two different processes” (Garber and Zhao 2002). The test statistic is the Z value, which is given as

$$Z = \frac{p_1 - p_2}{\sqrt{p(1-p)[(\frac{1}{n_1}) + (\frac{1}{n_2})]}}$$

Where

p_1 and p_2 = two proportions to be compared,

p = pooled estimated, and

n_1 and n_2 = population sample sizes.

$$p_1 = \frac{Y_1}{n_1}$$

$$p_2 = \frac{Y_2}{n_2}$$

$$p = \frac{Y_1 + Y_2}{n_1 + n_2}$$

Where Y_1 and Y_2 are the number of successes for population 1 and 2, respectively. The null hypothesis $H_0: p_1 = p_2$ was tested against that of $H_1: p_1 > p_2$. If the calculated Z statistic $> Z_\alpha$, which is the Z statistic corresponding to a significance level of α, then, the null hypothesis is rejected, and H_1 is accepted. A 5% significance level is normally used for the hypotheses tested Garber and Zhao 2002).

As one of statistical modeling techniques, regression modeling has been widely used for solving engineering problems. There are many different regression methods including: Liner Regression; Nonlinear Regression; and Logistic Regression. A few examples of utilizing regression methods to conduct crash analyses are described below.

Poisson and negative binomial models have been used to predict expected number of crashes in work zones. Venugopal and Tarko developed these models to predict the number of work zone crashes. They found that the traffic volume, length of the work zone, and duration of work were significant factors (Venugopal and Tarko 2000). In addition, the cost of the work zone and the type of work zone were also critical factors of work zone safety.

Another common practice is the use of multivariable statistical models. "A multivariable statistical model is an equation or set of equations that relate the expected number of crashes in a road with some characteristics of that road." "In essence, fitting a multivariable model is nothing else but estimating the expected number of crashes of some kind as a function of some selected independent variables, also called regressor variables or covariates." "These independent variables are specific characteristics of a roadway, such as traffic flow, road-section length, number of lanes, shoulder width, and others." "The method involves two basic steps: 1)selecting the model form or model equation, and 2) estimating the parameters. These two steps are usually repeated several times to enhance the model with each successive trial." "The basis of this multivariable regression method is the assumption that the expected crash frequencies are associated with causal factors in an orderly fashion" (Elias and Herbsman 2000).

The binary logistic regression method is a statistical technique developed for describing the relationship between a set of independent explanatory variables and a dichotomous response variable or outcome. "Since a binary logistic regression model is a direct probability model, which has no requirements on the distributions of the explanatory variables or predictors, it is more flexible and more likely to yield accurate results in traffic crash analyses" (Li and Bai 2009).

Many researchers have recognized the significance of logistic regression in the analysis of traffic safety. Hill (2003), Li and Bai (2006), and Dissanayake and Lu (2002) utilized the SAS software package to develop regression models and then organized them from the lowest to the highest severity. Their models took into account several important crash factors, such as "gender, driver impairment, and geometric conditions of crash sites" (Li and Bai 2009).

3.6 RESEARCH AND DEVELOPMENT TRENDS IN WORK ZONE SAFETY

Since the 1960s, the subject of work zone safety has become an attractive topic for many researchers. Results of previous research indicated that excessive speed and inattention driving were two major causal factors of work zone crashes. To improve the safety in work zones, vehicle speed control was determined by numerous researchers to be one of the best ways to improve safety in work zones. Many methods/devices have been developed and tested to control vehicle speeds. These include: Temporary Traffic Sign, Bump and Rumble Striping, Law Enforcement, Lane Width Reduction, Flagging, Radar Transmitter, Speed Monitoring Display, Portable Speed Display, Innovative Signs, and Changeable Message Sign. The literature review in this chapter described the previous studies on the effectiveness of these methods/devices in the work zones. Through the history, work zone safety improvement methods have been developed from passive to active, from physical to psychological, and from manual to automatic.

In the early studies, many researchers focused on how to reduce vehicles' speeds using external devices to draw drivers' attention. Rumble striping, lane width reduction, channelizing devices, and flashing lights of patrol cars were used to slow vehicles down. After the availability of digital display, some researchers utilized detective radar or drone radar with a display to remind the speeding drivers. In recent years, more researchers explored the use of innovative messages on the display to catch drivers' attention. Results of some lab experiments and travelers surveys indicated these innovative signs and messages were effective on reducing vehicle speeds. From the point of view of public travelers, this development process can be described as "from passive to active."

The process of "from passive to active" can also be translated into "from physical to psychological." Work zone traffic controls have become increasingly complex. Projects need numerous traffic control devices and other safety measures. However, results of crash tests under controlled laboratory conditions indicated certain traffic control devices and safety features could become a significant hazard; only those properly designed and installed devices performed well and presented little risk to vehicle occupants and workers (Bryden 1990; Hahn and Bryden 1980; and Mak et al. 1996). Bryden et al. pointed out about one-third of all work zone crashes in New York State from 1994 through 1996 were ones involved with work zone traffic control devices and safety features (Bryden et al. 1998). Since the appearance of CMS, it has been possible for engineers to convey more detailed information to travelers in dynamic way. To be more effective, researchers are concern about what message and format should be presented. All of these efforts aim at making drivers "positively" slow down after receiving the information.

Intelligent Transportation System (ITS) is an umbrella term for a collection of electronic, computing, and communication technologies that can be combined in various ways to increase the safety and mobility of the transport system and to reduce harm to the environment (Regan et al. 2001). Three broad categories of ITS can be discerned (Castro and Horberry 2004):

- Vehicle-based ITS technologies consist of sensors on the vehicle (e.g., radar, global positioning system) that collect traffic data, onboard units (OBUs) that receive and process these data, and display units that issue messages and warnings to the driver within the vehicle. A following distance warning system, for example, utilizes forward-looking radar to determine if the host vehicle is following a vehicle ahead too closely and warns the driver if this is so.

- Infrastructure-based ITS technologies consist of roadside sensors that collect traffic data, process the data on site or remotely, and then, transmit the results to the driver via roadside equipment, such as a Variable Message Signs (VMS). The advantage of these technologies over vehicle-based systems is that traffic information and warnings derived from the infrastructure-based ITS are available to all drivers. In addition, infrastructure-based ITS technologies can be used to collect traffic data that cannot be collected by vehicle-based systems under certain conditions such as the presence of fog on the road.
- Cooperative-based ITS technologies derive traffic data from the road infrastructure, from other vehicles on the road network, or from both sources and transmit the information to the drivers via VMS or via displays within the vehicle. Infrastructure-based ITS technologies, for example, can be used to detect a vehicle approaching an intersection and send a warning to other vehicles approaching the intersection about the presence of the first vehicle. Alternatively, vehicle-based ITS technologies in one vehicle can be used to warn another vehicle equipped with ITS technologies about its approaching to an intersection without any support from infrastructure-based systems.

In highway work zones, ITS technologies can be utilized in the following areas (FHWA 2006):

- Traffic monitoring and management
- Providing traveler information
- Incident management

- Enhancing safety of both the road user and worker
- Increasing capacity
- Enforcement
- Tracking and evaluation of contract incentives/disincentives (performance-based contracting)
- Work zone planning

There are many ITS application cases and some of them are presented in the following sub-sections.

3.6.1 Real-Time Work Zone Traffic Control System

The Real-Time Work Zone Traffic Control System (RTTCS) was used to support Illinois Department of Transportation (IDOT) work zone operations for a major bridge and highway reconstruction effort on Interstate 55 (I-55) in 2002 (FHWA 2004a). The RTTCS consisted of portable dynamic message signs (DMSs), portable traffic sensors, and portable closed circuit television cameras linked via wireless communications to a central workstation. The system monitored traffic along I-55, automatically generated messages on the DMSs based on predefined thresholds, provided data for a real-time congestion map displayed on IDOT's website, and provided congestion/incident detection alerts for IDOT staff. IDOT staff reported a high level of satisfaction with the RTTCS deployed in the I-55 work zone and believed that the system also provided safety benefits based on the decreased number of traffic violations after deployment and the small number of crashes that occurred in the work zone.

3.6.2 Dynamic Lane Merge System

The Michigan Department of Transportation (MDOT) rebuilt a large section of I-94 near Detroit during the 2002 and 2003 summer construction seasons. For this project, MDOT selected a Dynamic Lane Merge System (DLMS) to regulate merge movements and require early merging (FHWA 2004b). The system used microwave radar sensors installed on five DLM trailers to detect traffic volume, vehicle speed, and traffic density. Then, the system analyzed these data and automatically changed the messages displayed on the DMSs. With the deployment of DLMS in this project, MDOT observed a decrease in aggressive maneuvers and average peak period travel time. These outcomes improved both mobility and safety in the work zone, and ultimately met the goals of the deployment.

3.6.3 Work Zone Travel Time System

The Arizona Department of Transportation (ADOT) used a Work Zone Travel Time System (TTS) to support work zone operations during the reconstruction and widening of State Route 68 in northern Arizona (FHWA 2004c). The system consisted of two monitoring stations and a central processor. Each monitoring station included an inductive loop embedded in the roadway, a control cabinet with a communication system, and two digital cameras (one for each direction of traffic) linked to the cabinet via fiber-optic cable. The system relied on cameras to capture images of individual vehicles. After calculating vehicles' travel times through the work zone, ADOT staff estimated the progress of reconstruction and charged the contractors a disincentive fee when excessive delay occurred. By doing this, the contractors were forced to better manage their construction operations to mitigate the work zone travel delays and meet the travel time provision set by ADOT. Overall, both ADOT project managers and the contractors were satisfied with the performance of the system and the travel time incentive/disincentive clause.

3.6.4 Work Zone Traffic and Incident Management System

The New Mexico State Highway and Transportation Department (NMSHTD) reconstructed the Big I interchange in Albuquerque to make it safer and more efficient and to provide better access (FHWA 2004d). For this project, NMSHTD employed ITS in the form of a mobile traffic monitoring and management system to effectively move the large number of vehicles through the extensive construction area. The system, called Traffic and Incident Management System (TIMS), consisted of eight cameras, eight modular DMSs, four arrow dynamic signs, four all-light emitting diode (LED) portable DMS trailers, and four portable traffic management centers. The cameras detected real-time traffic conditions and sent the information to the traffic management center, where trained staff identified incidents and other adverse traffic conditions and immediately initiated appropriate responses. The use of TIMS for the Big I proved to be successful in mitigating the construction impact on traffic mobility and safety. This case is another example of how ITS is being implemented across the nation to help government agencies and contractors better manage traffic, while performing necessary infrastructure improvements.

3.7 SUMMARY OF LITERATURE REVIEW

How to improve the safety of work zones is a broad topic, from identifying the characteristics of work zone crashes to testing the effectiveness of specific devices or methods. Many researchers have conducted work zone safety studies for several decades.

The comprehensive literature review presented in this chapter covers several subjects in work zone safety including work zone crash characteristics, work zone traffic controls, statistical methods used in work zone studies, and research and development trends in work zone safety. Each subject was also divided into several subtopics. For example, crash characteristics in work zones included subtopics of crash rates, crash severity, crash location, crash type, and other crash characteristics.

Several researchers devoted their efforts to identifying work zone crash characteristics using statistical methods since this is the first step to understand work zone crashes. Most of these studies were statewide; a few studies did the analysis based on national data. Some studies emphasized crash rates, others focused on crash severity, and so on. Only a few projects conducted extensive analyses on all of these topics. Because of the limit on the data collection in different research projects, the conclusions were not consistent, even in one specific area. Among the findings, two conclusions were agreed upon in many studies: 1) truck-involved work zone crashes were more severe than other types of work zone crashes; and 2) crashes that occurred in rural highway work zones were more severe than those that happened in urban work zones.

Some studies evaluated the effectiveness of different work zone traffic control devices. One of the devices, a PCMS, is capable of conveying real time information to motorists and its effectiveness has been studied in several research projects. A PCMS could be an effective temporary traffic control device, if used appropriately. Compared with other temporary traffic control signs, the unique characteristic of conveying real time information makes the PCMS an efficient tool for improving work zone safety.

With the growing number of work zones nationwide, research on work zone safety continuously attracts attention from government agencies, engineering professionals, the transportation industry, and the traveling public. The utilization of ITS technologies in work zones has increased dramatically in recent years and this trend will be continued. It is reasonable to state that safety in work zones has been improving. However, there is room for continuous improvements.

Regarding rural highway work zone safety, the continuous improvements are much needed due to the number of severe crashes each year in the United States. The utilization of a PCMS in rural highway work zones holds great promise to improve safety based on the previous researches and projects results. For this reason, additional research efforts are needed to address several issues related to the utilization of a PCMS in rural work zones. First, the effectiveness of a PCMS on reducing vehicle speeds in the upstream of work zones needs to be determined. Second, the optimal deployment of a PCMS in the upstream of work zones should be defined based on vehicle speed profile models. Currently, the MUTCD does not specify where to install a PCMS in the upstream of work zones. Traffic engineers have to determine a location based on their experience which may not be accurate. Third, there is a need to understand drivers' reaction to a PCMS installed in rural work zones. Finally, there is a need to determine the effectiveness of a PCMS on reducing speeds of passenger cars and trucks because their different vehicle dimensions and driving behaviors.

CHAPTER 4: FIELD EXPERIMENT PHASE I

Along with the literature review, the field experiment Phase I was conducted in the summer of 2008 to collect vehicle speed data from two rural one-lane two-way highway work zones in Kansas. The primary objective of this field experiment was to determine the effectiveness of PCMS on reducing vehicles' speeds in the upstream of one-lane two-way work zones under three conditions: 1) the PCMS was turned on (PCMS on), 2) the PCMS was turned off, but still visible (PCMS off), and 3) the PCMS was out of sight (PCMS absent).

4.1 EXPERIMENTAL DEVICE AND LAYOUT

4.1.1 Speed Measurement System

Vehicle speeds were measured using two radar sensor systems. One system was set up upstream of the PCMS, and another one was installed downstream of the PCMS. A sensor system includes the following major components:

- One SmartSensor HD (model 125) unit equipped with power and data cables;
- One set of solar panels that charges two 12-volt batteries;
- One equipment/battery cabinet. This cabinet homes the central control panel for the smart sensor and the solar battery set;
- One laptop computer for data collection, monitoring, and downloading; and;
- One set of 12-foot temporary mounting post which consisted of a seven-foot top, a six-foot based, and three supporting anchors.

The sensor system is capable of collecting vehicles' speeds in up to ten lanes and uses microwave radar technology to detect speeds with minimum influence from environmental conditions. Both sensor systems were installed 8 to 12 feet (ft) away from the travel lane. This distance provided a relatively safe lateral clearance for passing traffic, the equipment and the researchers. In addition, this distance also complied with the manufacturer-recommended installation requirements. Results of field trials showed that this installation configuration enabled accurate speed collection, especially when the speeds of the passing vehicles were greater than 20 miles per hour (mph). Figure 4.1 shows the setup of a radar sensor system at one of the experimental sites. Table 4.1 presents the major technical specifications of the SmartSensor HD Model 125 unit, and Figure 4.2 shows a close-up picture of the smart sensor.

Figure 4.1 SmartSensor HD system

Table 4.1 Fact Sheet of SmartSensor HD Model 125

Category	Description
Installation	Relatively easy installation procedure. It can be mounted on an existing pole that provides proper height and distance.
Configuration	Auto configuration, low requirement for human adjustments.
Detection Range	Up to 10 traffic lanes, 6 to 250 ft.
Data Storage	Flash memory-based data storage.
Data Downloading	Wireless or cable downloading.
Operating Environment	Temperature: -40oC to 75oC; Humidity: up to 95% RH.
Maintenance	Minimum maintenance required.
Source: Wavetronix LLC. (2007). "SmartSensor 125 Cut Sheet." http://www.wavetronix.com/ support/smartsensor/125/documents/SS125_CutSheet.pdf. (Oct. 20, 2007).	

Figure 4.2 Close view of a SmartSensor HD

As illustrated in Figure 4.1, the SmartSensor HD unit was mounted on a mounting tripod approximately 12 ft above the ground. A 40-foot cable connected the sensor with the central control panel located in the cabinet. This cable also delivered the speed data to the data ports in the control panel. Two 12-volt batteries were stored in the cabinet, which could provide the required power to the sensor for eight consecutive days. To monitor real-time data collection and to process the data, a laptop computer was connected to the central control panel in the cabinet through a RS232 9-pin straight-through cable or a USB converter. In addition, the sensor was required to have horizontal and vertical orientations and lanes setup (direction, lane width, and lane location) for each installation to ensure proper function.

Although the SmartSensor HD system has functions, such as data storage and wireless data downloading, a laptop computer and a researcher assistant have to be employed on a real-time basis during the data collection due to the nature of field experiments. The speed comparison analyses must differentiate between different experimental conditions and set-ups. Therefore, each speed datum collected by the sensor system needs to be clearly verified with the proper judgment to ensure the speed belongs to the vehicle passing by. Also, the data have to be labeled under which conditions they are collected. As a result, a laptop computer and real-time human supervision are needed so that the measured speeds can be identified, and then, properly characterized.

In addition to the two radar sensor systems, a PCMS (model SMC1000) was utilized in the field experiment Phase I. The PCMS unit used in this experiment was a self-contained unit mounted on a trailer that could be towed by a light truck. The unit is battery operated with a solar panel, and has preprogrammed messages that can be displayed on the message board. The dimensions of the PCMS panel were 6.5 ft tall by 10 ft wide. Figure 4.3 shows the PCMS installed in one of the field experimental sites. The message on the PCMS changed from “SLOW DOWN” to “DRIVE SAFELY” every three seconds during the experiments. The PCMS was placed on the shoulder of the highway approximately 3 ft from the road on the side of the highway where drivers approached the work zone. Since the PCMS was located between the two sensor systems, the effectiveness of the PCMS on reducing vehicle speeds could be analyzed by the changes of vehicle speeds before and after the PCMS collected by the sensor systems.

Figure 4.3 The PCMS used in the field experiment Phase I

4.1.2 Field Experimental Layout

The placement of a PCMS in the upstream of the work zone depends on a sufficient distance that drivers can see the message on the PCMS and have enough time to take the required action. As stated in the Portable Changeable Message Sign Handbook, a minor action is a lane change by the motorist and a major action is for the motorist to make a detour from the current road (FHWA 2003). “For a minor action, the PCMS should be placed from 500 ft to 1,000 ft upstream of the decision point, regardless of speed” (FHWA 2003). In this field experiment, the decision point was defined as the location of the first MUTCD defined temporary traffic sign (TTS) in the upstream of the work zones. This TTS was the W20-1 sign: Road Work Ahead. Since drivers were required to take only minor actions after seeing the PCMS, therefore, the PCMS was placed 750 ft upstream of the first TTS.

A key element for an accurate speed measurement was the proper location of the speed sensor system. The placement of the sensor was at a location that would help to better understand the drivers’ reactions after they recognized the messages on the PCMS. Assuming the PCMS was effective, motorists approaching to the work zone would drive more cautiously. Presumably, drivers would 1) begin reducing their speeds earlier, 2) reduce their speeds more rapidly, or 3) decelerate their vehicles both earlier and more rapidly. Any of the three reactions would result in a lower speed at a certain stage during the deceleration process. Because the success of the experiments greatly depended on the capture of vehicle speeds at locations where pronounced speed differences would occur given the PCMS was effective, the two sensor systems were set up at the highway locations where vehicles would likely decelerate from 65 mph (speed limit) to 45 mph.

As shown in Figure 4.4, Sensor 1 was installed 1,050 ft away from the first TTS with the message *Road Work Ahead*. Sensor 2 was installed 550 ft away from the first TTS. The PCMS was placed between the two sensors and was 200 ft away from Sensor 2. This layout was used for test conditions one (PCMS on) and two (PCMS off). The experimental layout remained the same for test condition three (PCMS absent) except there was no PCMS present as shown in Figure 4.5.

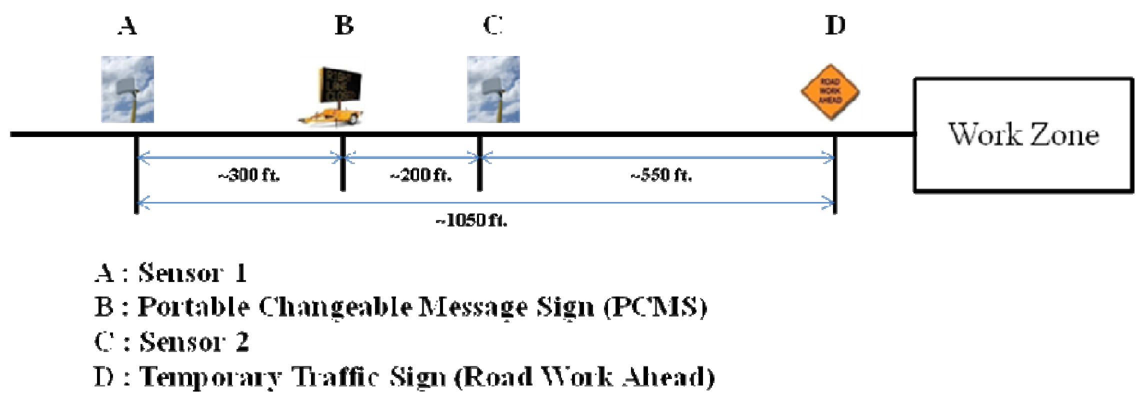


Figure 4.4 Experimental layout for test conditions 1 and 2

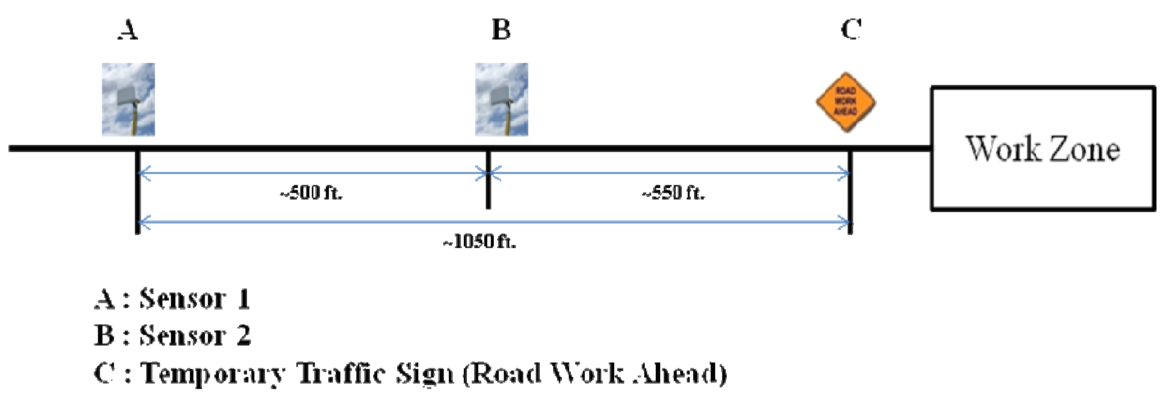


Figure 4.5 Experimental layout for test condition 3

4.2 DESCRIPTIONS OF WORK ZONE SITES

Field experiment Phase I was conducted at two sites. Both of them were one-lane two-way work zones on rural two-lane highways with speed limits of 65 mph. Other than the availability, the two work zones selected for experiments Phase I had to meet the following requirements.

- It had to be a one-lane two-way rural highway work zone. Roadway type and work zone configurations are important for speed research. The traffic flows on urban two-lane roadways are considerably affected by factors, such as high traffic volumes and traffic signals. The speed limits for these highways are typically low (i.e., lower than 55 mph). Rural highways, on the other hand, do not have these limitations. In addition, work zones with multiple open lanes do not require traffic to stop and, consequently, may not suffer as severely from rear-end collision problems as one-lane two-way work zones, where complete stops are required for through traffic.
- Traffic volume should be moderate. Traffic characteristics, exclusively traffic volume, were critical factors for the success of this study. The limited traffic volume will ensure that the measurements are vehicle free-flow speeds.
- The minimum safety conditions must be met. "The PCMS normally is placed on or just outside the shoulder. A PCMS can become a roadside hazard if not protected from an errant vehicle" (FHWA 2003). The space must be available for setting up the PCMS without interfering with the traffic flow, and research personnel must be able to safely collect data.

The first selected work zone was located on highway US-36 between K-87 and K-63, as shown in Figure 4.6. This highway section was a two-lane highway road with a speed limit of 65 mph in northeast Kansas between Marysville and Seneca. The traffic volume on US-36 was 3,630 vehicles per day (vpd). The construction project took place in early June of 2008 and was a paving (chip and seal) operation to rehabilitate the roadway surface. The project required one traffic lane to be closed to overlay the pavement, while the other lane was kept in service. A flagger was used at each end of the work zone for traffic control and a pilot vehicle, shown in Figure 4.7, was employed to guide through traffic. The two stop locations at both ends were moved approximately 3 to 4 times per day depending on the construction progress. Experiments were conducted at this work zone from June 3, 2008 to June 6, 2008.

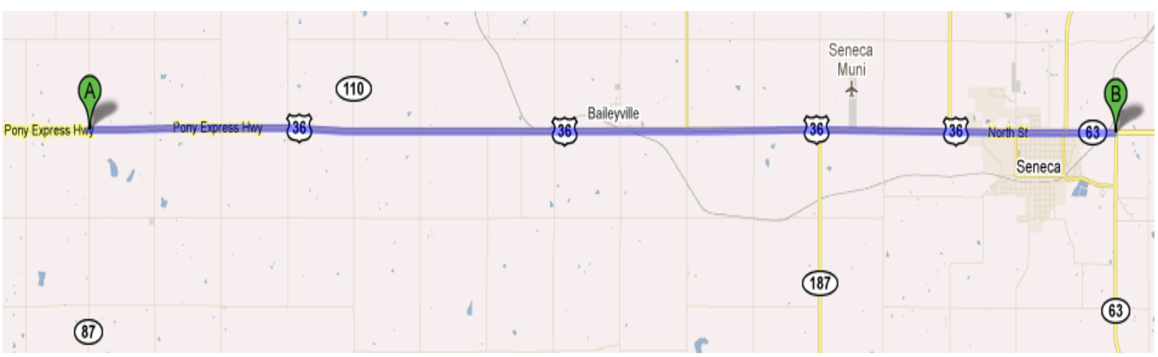


Figure 4.6 Work zone on US-36 between K-87 and K-63

Figure 4.7 A pilot car used in the US-36 work zone

The second selected work zone was located on US-73 between Hiawatha and Horton, Kansas, as shown in Figure 4.8. This work zone was also on a two-lane highway with a speed limit of 65 mph in northeast Kansas. The annual average daily traffic along selected highway section was approximately 3,400. A paving operation was also performed in this work zone in order to rehabilitate the roadway surface. A flagger was used to control traffic at each end of the work zone and every major highway entrance in between. Two stop locations at each end were moved 3 or 4 times per day depending on the construction progress. A pilot car was utilized to guide traffic safely through the work zone. Experiments were conducted at this work zone from June 9, 2008 to June 11, 2008. While construction operations were underway, the two-lane highway was reduced to a one-lane two-way work zone. The layout of the two work zones is shown in Figure 4.9. The start of experimental location (Sensor 2 in Figure 4.4 and Figure 4.5) was located 550 ft upstream of the first TTC sign (W20-1 shown on the left side in Figure 4.9) in order to avoid disturbing the effect of the traffic control device and to exclusively test the effectiveness of PCMS.

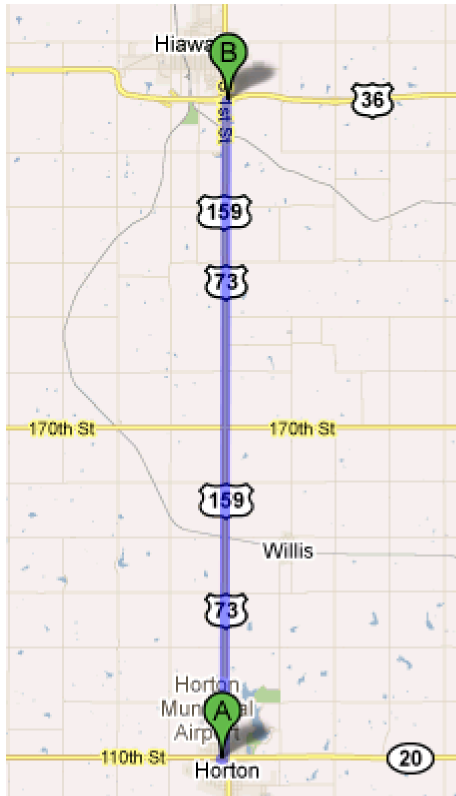


Figure 4.8 Work zone on US-73 between Hiawatha and Horton

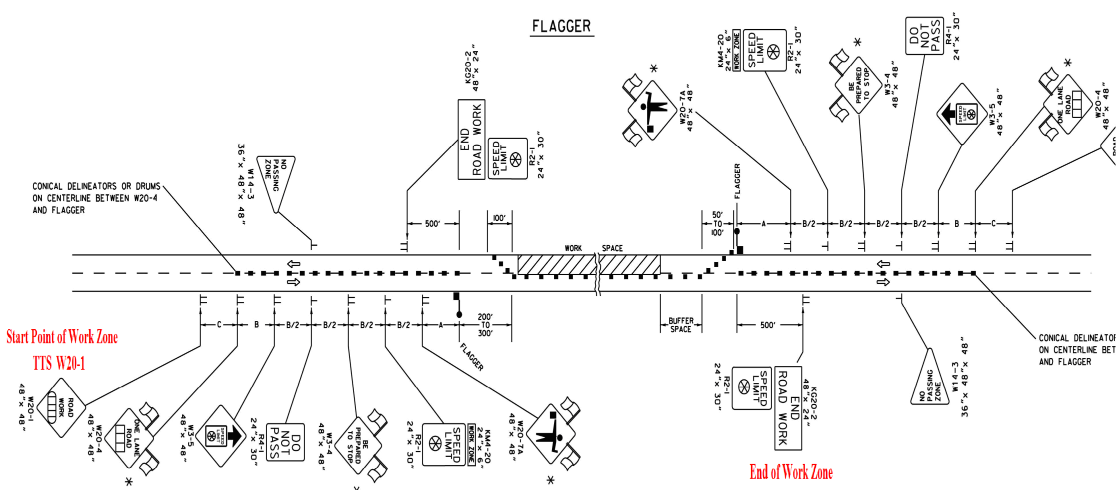


Figure 4.9 The work zone layout on US-36 and US-73

4.3 DATA COLLECTION

The vehicle speed data were collected using the smart sensor systems as introduced before. When the speed of a passing vehicle was captured, the sensor sent the speed datum to the connected laptop computer in real time and the computer displayed the speed on a graphic interface that simulated the passing vehicle labeled with its speed. A research assistant examined each speed datum displayed on the computer, and then, either accepted the datum, if it was correctly detected, or discarded it, if it was incorrectly measured. External factors, which occasionally interfered with passing vehicles and caused the data to be incorrectly recorded, included the inferences of pedestrians, low-speed farm vehicles, and construction-related vehicles that either had very low speed or whose drivers had been well aware of the upcoming work zone conditions. In addition, the speed of a vehicle must be recorded by both Sensor 1 and Sensor 2 (in a pair). If only one sensor recorded a vehicle speed and another sensor didn’t, then the single speed datum had to be discarded. The speeds were matched by verifying the difference of the computer times and drawing a correlation between the data from Sensor 1 and Sensor 2.

The sensors produced raw data files in a text file format (.txt file) and classified the data by lanes, length of vehicle, speed, vehicle class, range, date and time as shown in Figure 4.10. The raw data collected from the field experiments went through an extensive screening process, described as follows. The raw data was first thoroughly screened by matching individual vehicle data points recorded on both Sensors 1 and 2. Any vehicle that did not have a corresponding data point from both sensors was discarded. In addition, a data point was discarded from the data population if accurate vehicle length, speed, or any other value was not recorded by one of the sensors, regardless if there were two corresponding data points. Finally, any data point that recorded a vehicle speed under 20 mph was omitted from the data set because the sensors were unable to properly record speeds under 20 mph according to the sensor specifications. Through this initial data screening, the raw data were condensed and sorted before using a statistical analysis program to perform further calculations and analysis.

```
####################################################################
#                                                                  #
#             DATE         : June 03, 2008                         #
#             SERIAL NUMBER: SS125 U100000378                      #
#             DESCRIPTION  : SS125 ITS Radar                       #
#             LOCATION     : US-36                                 #
#             ORIENTATION  : North                                 #
#__________________________________________________________________#
#          |        |       |       |       |      SENSOR TIME     #
# LANE     | LENGTH | (MPH) | CLASS | RANGE | YYYY-MM-DD HH:MM:SS.sss #
#          |        |       |       |       |                      #
####################################################################
  LANE_01       76      48      4       36    2008-06-03 10:28:50.200
  LANE_01       45      38      3       35    2008-06-03 10:30:35.195
  LANE_01       20      37      2       37    2008-06-03 10:31:30.457
  LANE_01       21      47      2       38    2008-06-03 10:31:48.408
  LANE_01       22      49      2       37    2008-06-03 10:31:56.469
  LANE 01       19      46      1       37    2008-06-03 10:33:07.094
```

Figure 4.10 Example of the text file

Table 4.2 shows an example of the speed datasheet from Sensor 1. In addition to the sensor number, the datasheet also included the following relevant traffic variables: 1) Lane: This was a variable indicating the lane which the vehicle passed through. The sensor has the capability of capturing up to 10 lanes. For this project, experiments were conducted in two-lane work zones. 2) Length: This variable indicated the vehicle length detected by the sensor. 3) MPH: This variable was the speed of a vehicle as it passed the location of a sensor. 4) CLASS: This variable indicated the type of vehicle passing a sensor. The sensor can classify the vehicle class based on its length. 5) RANGE: This variable was a secondary variable to verify the classification of the data in the initial data collection. 6) YYYY-MM-DD: This variable indicated the year, month, and day the speed was recorded. 7) HH:MM: SS.SSS: This variable indicated the time when a vehicle passed a sensor. This variable was used to match the speed data between Sensors 1 and 2.

Table 4.2 An Example of the Speed Datasheet

Sensor 1						
LANE	LENGTH	(MPH)	CLASS	RANGE	YYYY-MM-DD	HH:MM:SS.sss
LANE_01	15	15	1	20	6/13/2008	11:17:56
LANE_01	27	19	2	19	6/13/2008	12:36:39
LANE_01	17	27	1	19	6/13/2008	12:46:00
LANE_01	19	31	1	18	6/13/2008	11:11:58
LANE_01	21	31	2	20	6/13/2008	11:15:29
LANE_01	22	32	2	22	6/13/2008	11:53:22
LANE_01	17	34	1	20	6/13/2008	11:02:09
LANE_01	18	34	1	18	6/13/2008	11:11:54

A total of 976 vehicle speed data were collected in the two work zones. Of these, 358 vehicle speed data were captured with the PCMS on, 435 were collected with the PCMS off, and 183 were collected when the PCMS was removed from the highway. Table 4.3 shows the list of data collected on US-36 from June 2 to June 6, 2008 and on US-73 from June 9 to June 13, 2008. Field experiments were started on US-36 (a short-term work zone project). When the construction work finished on US-36, there were only 31 data points for the PCMS absent condition. Clearly, 31 data points were not enough to do a statistical analysis. Thus, additional data were collected in a work zone at US-73, a nearby highway identical to the US-36.

Table 4.3 Speed Data by Different Experimental Sites

Work Zone	**Average Daily Traffic Volumes**	**Speed Limit (mph)**	**PCMS On**	**PCMS Off**	**PCMS Absent**
US-36	3,630	65	358	435	31
US-73	3,400	65	0	0	152
Total			358	435	183

4.4 DATA ANALYSIS OF EXPERIMENT PHASE I

The major task that needed to be accomplished in the data analysis was the evaluation of the vehicle speed changes under three experimental conditions in two work zones. If the vehicle speeds significantly reduced from Sensor 1 location to Sensor 2 location when the PCMS was present, then, it could be concluded that the PCMS was an effective traffic control device that could be utilized to improve safety in two-lane work zones.

4.4.1 Frequency Analysis on Vehicle Speed

Analyses of the distributions of speeds with the PCMS on, PCMS off, and PCMS absent were conducted to demonstrate the effectiveness of the PCMS. The basic assumption was that, if the PCMS was effective, it would reduce the number of speeding drivers approaching the work zones. If the distribution of the speeds recorded when the PCMS was on illustrated a pronounced reduction in the number of notably high speeds, then it could be concluded that the PCMS was able to more effectively reduce the speeding drivers' behavior when approaching work zones. The Figures 4.11, 4.12 and 4.13 show the distribution speeds by 5 mph speed intervals when PCMS on, off and absent, respectively.

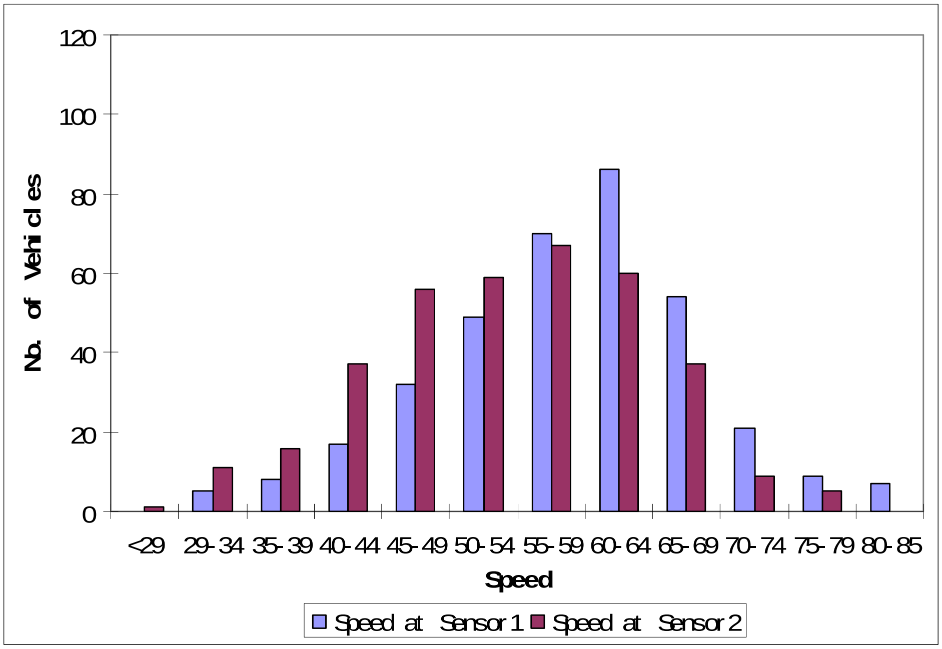


Figure 4.11 Distribution speeds by 5-mph speed intervals with PCMS On

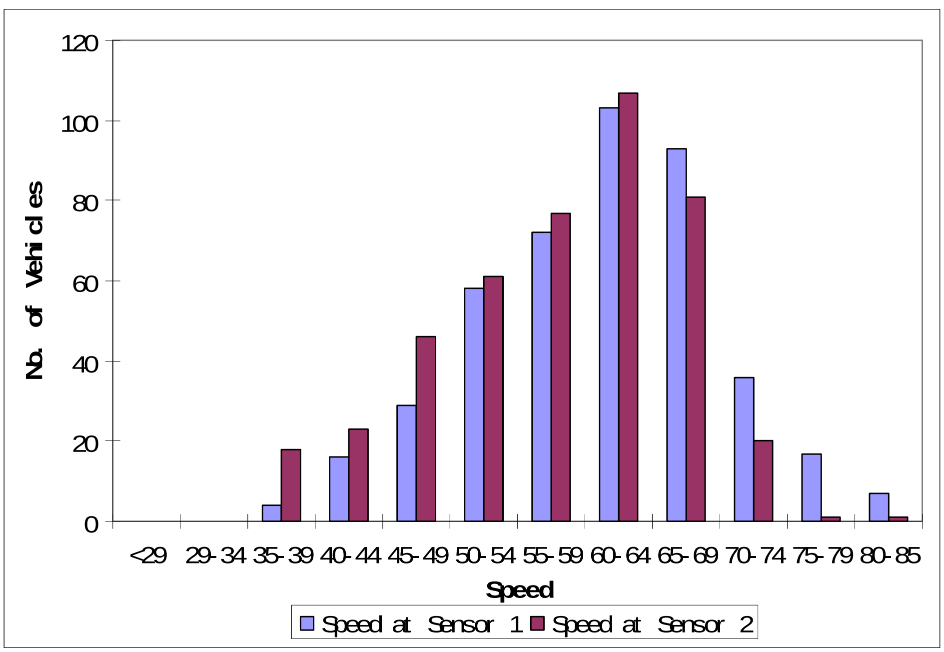


Figure 4.12 Distribution speeds by 5-mph speed intervals with PCMS Off

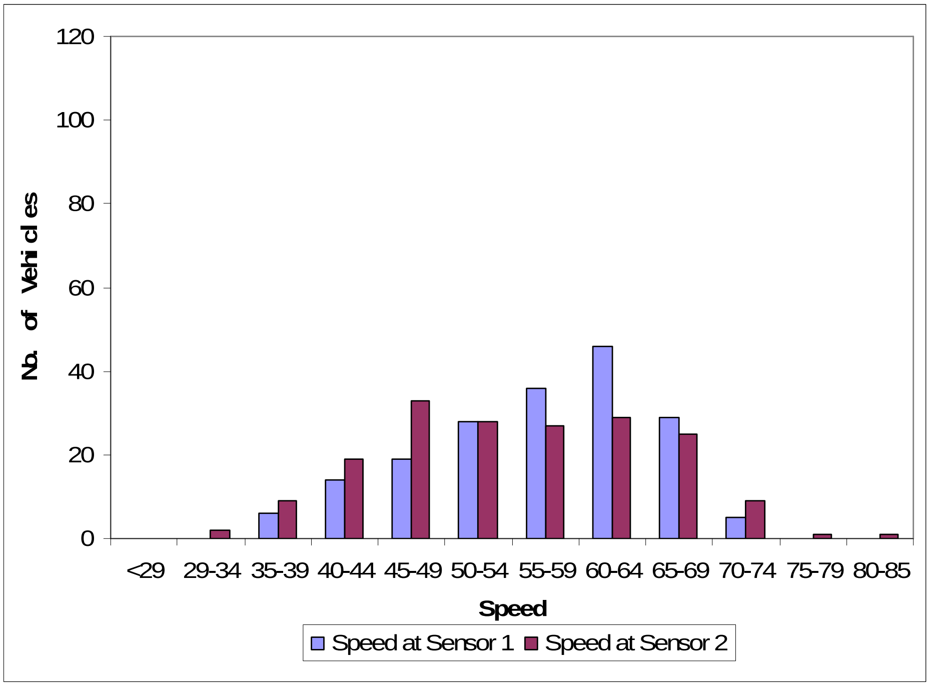


Figure 4.13 Distribution speeds by 5-mph speed intervals without PCMS

When the PCMS was on, the speeding vehicle percentage (speed > 65 mph) at the Sensor 1 location was 25.4%. After the vehicles had passed the PCMS, the speeding vehicle percentage was 14.2% at the Sensor 2 location, showing an 11.2% reduction. When the PCMS was off, the speeding vehicle percentage at Sensor 1 was 35.2%. After the vehicles had passed the PCMS, the speeding vehicle percentage at Sensor 2 was 23.7%, showing an 11.5% reduction. When the PCMS was absent from the road, the speeding vehicle percentage at Sensor 1 was 18.6%. After the vehicles had passed the PCMS, the speeding vehicle percentage at Sensor 2 rose to 19.7%, showing a 1.1% increase. Table 4.4 shows the speeding vehicle percentage changes from Sensors 1 to 2 under three experimental conditions.

Table 4.4 Percentage of Speeding Vehicle Changes

	Speeding vehicle percentage at Sensor 1	Speeding vehicle percentage at Sensor 2	Change of speeding vehicle percentage
PCMS On	25.4%	14.2%	11.2%
PCMS Off	35.2%	23.7%	11.5%
PCMS Absent	18.6%	19.7%	-1.1%

Note: "-" means a increase in percentage

The 85th-percentile speed, a major parameter used by traffic engineers, is the speed that reasonable people tend to adopt according to the road environment. Table 4.5 shows the reduction of the 85th-percentile speed under three conditions. There were 4 mph, 2 mph, and 0 mph speed reductions of 85th percentile speed under three conditions; this trend again proved that the PCMS was effective on reducing vehicle speeds. However, the percentage of speeding vehicle reductions shows that under the PCMS off condition, a remarkable reduction (8.7% for exceeding 5 mph and 5.1% for exceeding 10 mph) happened. It was interesting to find that the deactivated PCMS slowed down more speeding vehicles than the activated PCMS. The different sample sizes under these two conditions may be responsible for this outcome.

Table 4.5 Reduction of 85th Percentile Speeds

Measure of Effectiveness	Speed Reduction PCMS On	Speed Reduction PCMS Off	Speed Reduction PCMS Absent
85th-percentile speed Reduction	4 mph	2 mph	0 mph
% of vehicles exceeding speed limit by 5 mph	6.4%	8.7%	-3.3%
% of vehicles exceeding speed limit by 10 mph	3.1%	5.1%	-1.1%

Note: "-" means a increase in percentage

Table 4.6 shows the speed changes by percentage and mph under three conditions. When the PCMS was on, about 19.3% of the vehicles increased the speed from 1 mph to 10 mph between Sensor 1 and Sensor 2; 5.3% of the vehicles kept the same speed; and

75.6% of the vehicles slowed down from a range of 1 mph to 32 mph. When the PCMS was turned off, about 20.2% of the vehicles increased speed from a range of 1 mph to 16 mph between Sensor 1 and Sensor 2; 10.1% of the vehicles kept the same speed; and 69.7% of the vehicles slowed down from a range of 1 mph to 38 mph. When there was no PCMS on the road, about 32.8% of the vehicles increased the speed from a range of 1 mph to 29 mph between Sensor 1 and Sensor 2; 7.1% of the vehicles kept the same speed; and 60.1% of the vehicles slowed down from a range of 1 mph to 25 mph. These results provide additional proof of the effectiveness of the PCMS. Based on the results of the frequency analyses, it was concluded that the PCMS (on and off) attracted a larger proportion of the speeding drivers' attention. As a result, a larger percentage of speeding reduction was observed when the PCMS was on or off comparing with the condition of PCMS absent.

Table 4.6 Speed Change by Percentage and MPH under Different Conditions

	Speed Increase %	**Same Speed %**	**Speed Decrease %**	**Min Speed Increase mph**	**Max Speed Increase mph**	**Min Speed Decrease mph**	**Max Speed Decrease mph**
PCMS On	19.3	5.3	75.6	1	10	1	32
PCMS Off	20.2	10.1	69.7	1	16	1	38
PCMS Absent	32.8	7.1	60.1	1	29	1	25

4.4.2 Comparison Analysis

Three comparison analyses were conducted to test vehicle mean speed changes under the three experimental conditions including: A comparison of vehicle mean speed change under the conditions of PCMS on and off; A comparison of vehicle mean speed change under the conditions of PCMS on and absent; and A comparison of vehicle mean speed change under the conditions of PCMS off and absent.

The two-sample t-test was utilized for the comparison analyses. Figures 4.14, 4.15, and 4.16 show the distributions of vehicle speed data at the location of Sensors 1 and 2 for the three experimental conditions. Figure 4.17 presents the mean speed comparison between Sensors 1 and 2 for the three conditions.

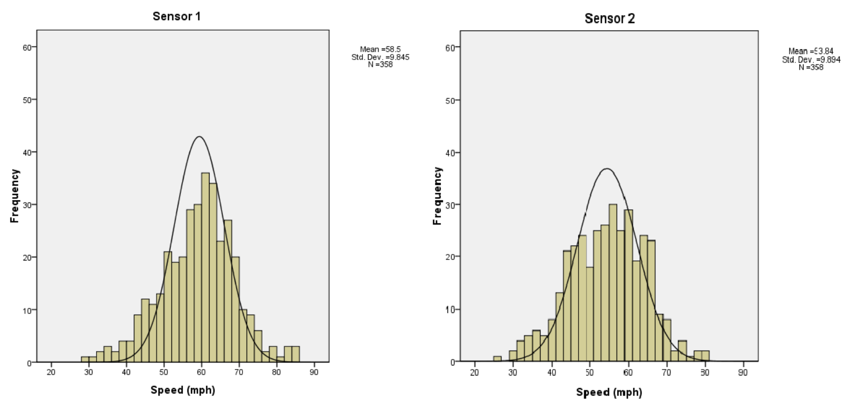


Figure 4.14 Data distribution of Sensors 1 and 2 under condition of PCMS On

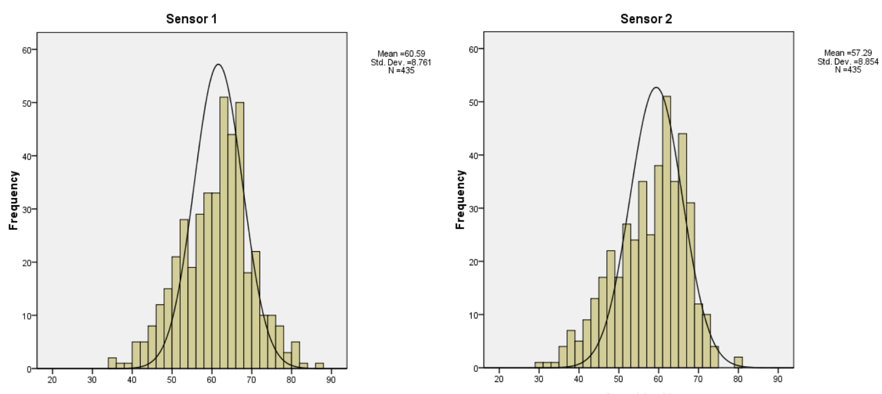


Figure 4.15 Data distribution of Sensors 1 and 2 under condition of PCMS Off

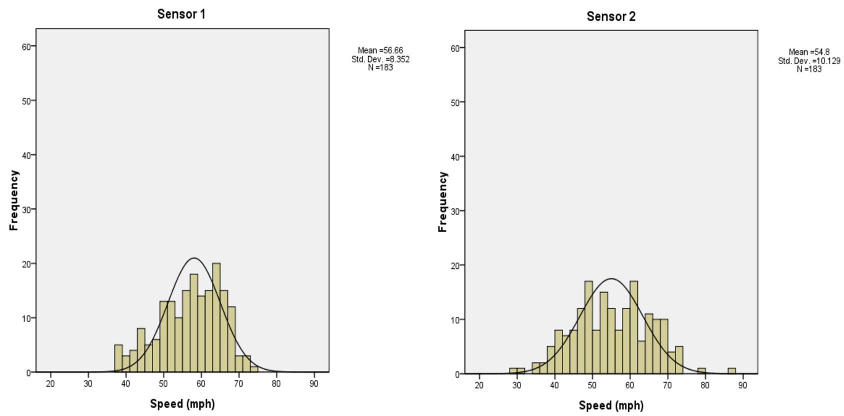


Figure 4.16 Data distribution of Sensors 1 and 2 under condition of PCMS Absent

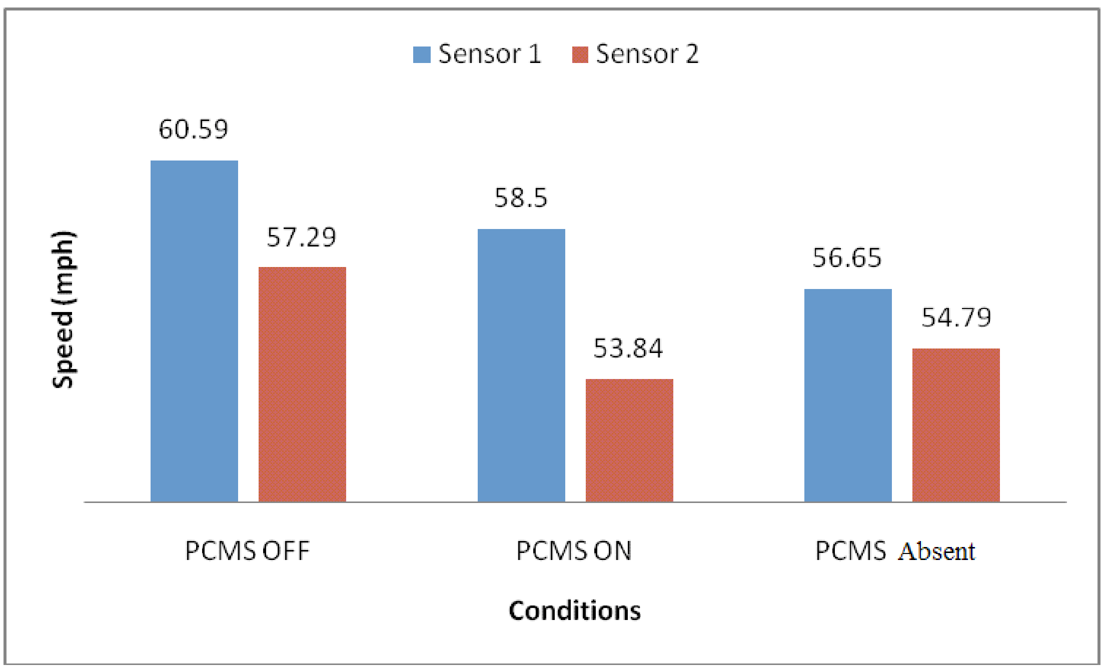


Figure 4.17 Mean speed comparison for three conditions

4.4.2.1 Comparison between PCMS On and Off

The number of speed data collected (population) from the two sensors, when the PCMS was on and off, were 358 and 435, respectively. Under the condition of PCMS on (Condition 1), the mean vehicle speed at Sensor 1 was 58.5 mph with a standard deviation of 9.85 as shown in Table 4.7. The mean vehicle speed at Sensor 2 was 53.8 mph with a standard deviation of 9.89. These values clearly show an 8.0 % or 4.7 mph speed reduction from Sensor 1 to Sensor 2.

Table 4.7 Statistical Values for Three Experimental Condtions

	Condition 1 (PCMS on)		**Condition 2 (PCMS off)**		**Condition 3 (PCMS absent)**	
	Sensor one	Sensor two	Sensor one	Sensor two	Sensor one	Sensor two
Population	358		435		183	
Mean Speed (mph)	58.5	53.8	60.6	57.3	56.7	54.8
Median Speed (mph)	59	54	62	59	58	55
Standard Deviation	9.85	9.89	8.76	8.85	8.35	10.12
Min Speed (mph)	29	26	35	30	38	29
Max Speed (mph)	85	79	86	80	74	87
Reduction in Mean Speed (mph)	4.7		3.3		1.9	
Percent Reduction in Mean Speed (%)	8.0		5.5		3.4	

Under the condition of PCMS off (Condition 2), the statistic values also indicated a decreasing pattern, but not as large as when PCMS was turned on. The mean vehicle speed at Sensor 1 was 60.6 mph with a standard deviation of 8.76 as shown in Table 4.7. The mean vehicle speed at Sensor 2 was 57.3 mph with a standard deviation of 8.85. The percent reduction was 5.5 %.

For the first comparison analysis (also called Case 1 hereafter), a null hypothesis (H_0) and an alternative hypothesis (H_1) are defined as follows:

(Case 1)

$$H_0 : (\mu_{O1} - \mu_{O2}) \leq (\mu_{F1} - \mu_{F2})$$

$$H_1 : (\mu_{O1} - \mu_{O2}) > (\mu_{F1} - \mu_{F2})$$

Where μ_{O1} or μ_{O2} = mean vehicle speed at Sensor 1 or Sensor 2 when the PCMS was on; and μ_{F1} or μ_{F2} = mean vehicle speed at Sensor 1 or Sensor 2 when the PCMS was off. The null hypothesis is interpreted as the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS on is no larger than that of the condition of PCMS off. The alternative hypothesis is interpreted as the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS on is larger than that of the condition of PCMS off. A 5 % (0.05) level of confidence is used in the t-test. In other words, if the result of the t-test indicates a P-value is less than 0.05, then, the null hypothesis can be confidently rejected in favor of the alternating hypothesis. Table 4.8 shows the results of the t-test for Case 1. Based on the results, it was concluded that the null hypothesis of Case 1 was confidently rejected in favor of the alternative hypothesis because the P-value was less than 0.05. In other words, the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS on was larger than that of the condition of PCMS off.

Table 4.8 Results of Two-Sample t-test for Mean Speed Change between PCMS On and Off

Cases	Conditions	Population	P-value	Effectiveness
1	PCMS on	358	0.002	Yes
	PCMS off	435		

4.4.2.2 Comparison between PCMS On and PCMS Absent

The speed data collected at the first experimental location, US-36 between Seneca and Marysville, Kansas, were predominantly data with the PCMS present (PCMS on or off). The second location, US-73 between Horton and Hiawatha, Kansas, was used to collect additional speed data points when the PCMS was absent (Condition 3 in Table 4.7). The statistic values for condition 3 indicated the smallest decrease of mean vehicle speed from Sensor 1 to Sensor 2. As listed in Table 4.7, the mean vehicle speed at Sensor 1 was 56.7 mph with a standard deviation of 8.35. The mean vehicle speed at Sensor 2 was 54.8 mph with a standard deviation of 10.12. The reduction percentage was 3.4%.

For the second comparison analysis (also called Case 2 hereafter), the null hypothesis (H_0) and the alternative hypothesis (H_1) are defined as follows:

(Case 2)

$$H_0 : (\mu_{O1} - \mu_{O2}) \leq (\mu_{N1} - \mu_{N2})$$

$$H_1 : (\mu_{O1} - \mu_{O2}) > (\mu_{N1} - \mu_{N2})$$

Where μ_{O1} or μ_{O2} = mean vehicle speed at Sensor 1 or Sensor 2 when the PCMS was on; and μ_{N1} or μ_{N2} = mean vehicle speed at Sensor 1 or Sensor 2 when the PCMS was removed from the highway. The null hypothesis is interpreted as the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS on is no larger than that of the condition of PCMS absent. The alternative hypothesis is interpreted as the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS on is larger than that of the condition of PCMS absent. Same as the first comparison test, a 5 % (0.05) level of confidence was used in the t-test.

Table 4.9 shows the results of the t-test for Case 2. Based on the results, it was concluded that the null hypothesis of Case 2 was confidently rejected in favor of the alternative hypothesis because the P-value was less than 0.05. In other words, the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS on was larger than that of the condition of PCMS absent.

Table 4.9 Results of Two-Sample t-test for Mean Speed Change between PCMS On and Absent

Cases	Conditions	Population	P-value	Effectiveness
2	PCMS on	358	0.000	Yes
	Without PCMS	183		

4.4.2.3 Comparison between PCMS Off and PCMS Absent

For the third comparison analysis (also called Case 3), the null hypothesis (H_0) and the alternative hypothesis (H_1) are defined as follows:

(Case 3)

$$H_0 : (\mu_{F1} - \mu_{F2}) \leq (\mu_{N1} - \mu_{N2})$$

$$H_1 : (\mu_{F1} - \mu_{F2}) > (\mu_{N1} - \mu_{N2})$$

Where μ_{F1} or μ_{F2} = mean vehicle speed at Sensor 1 or Sensor 2 when the PCMS was off; and μ_{N1} or μ_{N2} = mean vehicle speed at Sensor 1 or Sensor 2 when the PCMS was removed form the highway. The null hypothesis is interpreted as the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS off is no larger than that of the condition of PCMS absent. The alternative hypothesis is interpreted as the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS off is larger than that of the condition of PCMS absent. As usual, a 5 % (0.05) level of confidence was used in the t-test.

Table 4.10 shows the results of the t-test for Case 3. Based on the results, it was concluded that the null hypothesis of Case 3 was confidently rejected in favor of the alternative hypothesis because the P-value was less than 0.05. In other words, the mean vehicle speed change from Sensor 1 to Sensor 2 under the condition of PCMS off was larger than that of the condition of PCMS absent.

Table 4.10 Results of Two-Sample t-test for Mean Speed Change between PCMS Off and Absent

Cases	Conditions	Population	P-value	Effectiveness
3	PCMS off	435	0.005	Yes
	Without PCMS	183		

In summary, there is a decreasing pattern for all of the three conditions shown in Table 4.7. The normally distributed sample dataset and unequal variances allowed the use of the t-test to determine the significances for three cases. Using SPSS software to calculate the significance, the P-values were 0.002 for Case 1, 0.000 for the Case 2, and 0.005 for the Case 3. Since these values are significantly less than 0.05, it was concluded that all three null hypotheses were confidently rejected. Thus, all three alternative hypotheses were statistically true.

4.4.3 Comparison of Mean Speed Changes between Passenger Car and Truck

The vehicles classes were determined using AASHTO Green Book definitions (AASHTO 2004). Therefore, the passenger car class includes any vehicle with an average length of 19 ft or less, and the truck class includes any vehicle with an average length equal to or greater than 19 ft. After the individual speed data were sorted by vehicle classes, statistical analyses were performed.

4.4.3.1 Frequency Analyses

The frequency of individual vehicle speed changes, sorted by vehicle classes (Passenger Car and Truck), are shown in Figure 4.18 and Figure 4.19. Each histogram contains a bell curve which represents a normal distribution of the data set. Table 4.11 shows the results of mean speed changes based on the vehicle class under three experimental conditions. The speeds of 395 passenger cars and 581 trucks were recorded during field experiments.

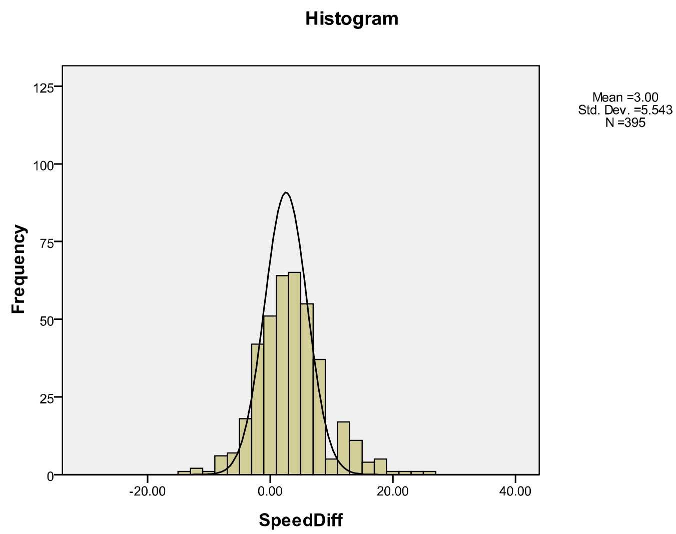


Figure 4.18 Frequency of speed change for passenger cars

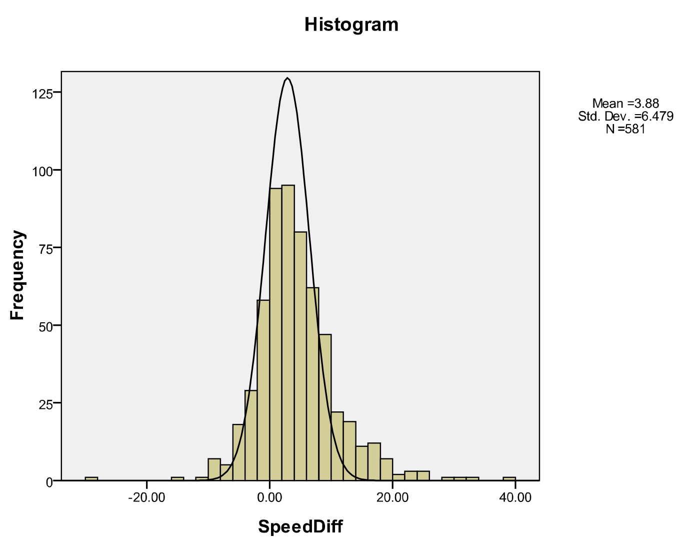


Figure 4.19 Frequency of speed change for trucks

Table 4.11 Mean Speed Changes Based on Vehicle Class

Vehicle Class	Case	N	Sensor 1 Speed (mph)	Sensor 2 Speed (mph)	Mean Speed Change (mph)	Speed Change Percentage
Passenger Cars	PCMS On	132	58.5	54.5	4.0	6.8%
	PCMS Off	188	60.2	57.9	2.3	3.8%
	PCMS Absent	75	57.0	54.0	3.0	5.3%
Trucks	PCMS On	226	58.5	53.5	5.0	8.5%
	PCMS Off	247	60.9	56.9	4.0	6.6%
	PCMS Absent	108	56.4	55.4	1.0	1.8%

For passenger cars and trucks, the speed reductions were 2.3 mph and 4.0 mph, respectively, over a distance of 500 ft when the PCMS was off. When the PCMS was on, passenger cars and trucks showed speed reductions of 4.0 mph and 5.0 mph over a distance of 500 ft, respectively. The activated PCMS reduced the mean speed of trucks more than the mean speed of passenger cars. In addition, the results indicated that the speed reductions of passenger cars and trucks increased 1.7 mph and 1.0 mph, respectively, when the PCMS was on comparing with the results of PCMS off. Passenger cars and trucks experienced speed reductions of 3.0 mph and 1.0 mph, respectively, over a distance of 500 ft when the PCMS was absent.

As shown in Table 4.11, the greatest speed reductions for passenger cars and trucks occurred when the PCMS was on. The changes in mean speeds for the different vehicle classes under three experimental conditions are shown in Figure 4.20. The bar chart indicates that the mean speed of trucks was reduced more than the mean speed of passenger cars when the PCMS was on or off. It also indicates that the mean speed of trucks was reduced less than the mean speed of passenger cars when the PCMS was absent.

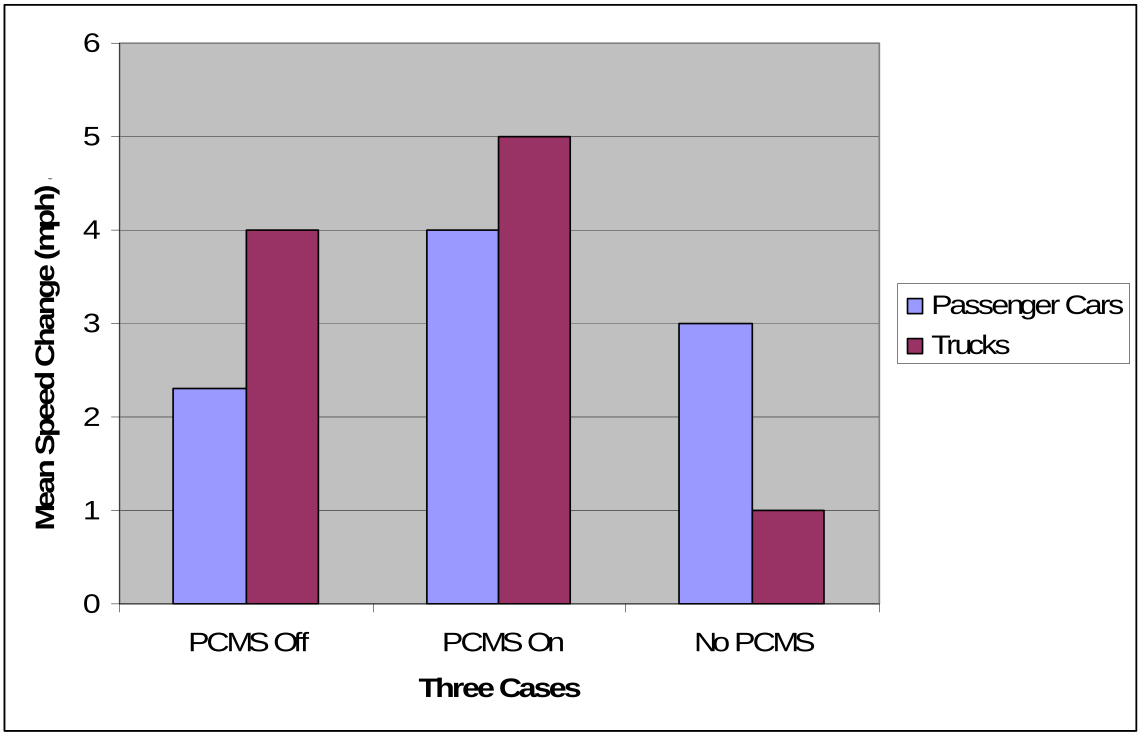


Figure 4.20 Mean speed change of vehicle classes for three cases

4.4.3.2 Significance of Test Analysis

Besides frequency analysis, hypothesis tests were conducted to compare the difference of mean speed changes between passenger cars and trucks under the three experimental conditions. The null hypothesis was that there was no difference between conditions in the mean speed changes of the two vehicle classes. The alternative hypothesis was that there was a difference between conditions in the mean speed changes of one or more of the vehicle classes. A univariate analysis of variance (UNIANOVA) was performed on the data to determine whether the interaction between the three conditions and the two vehicle classes was significant. UNIANOVA is a two-way analysis of variance with the vehicle class and the experimental conditions as the two factors. The results of the UNIANOVA test are shown in Table 4.12 and are based on a

95% confidence level. Since the UNIANOVA test returned a significance value of 0.000 for the three conditions (On_Off_Not) and a significance value of 0.003 for the interaction of three conditions and two vehicle classes (VehicleClass*On_Off_Not), the null hypothesis was rejected in favor of the alternative hypothesis. In other words, there was a difference between conditions in the mean speed changes of one or two of the vehicle classes.

Notice that the R square value is 0.042, this small number shows that 4.2 percent of the total mean speed changes variance is accounted by the main effects due to vehicle class, main effects due to experiment condition, and the interaction effect due to vehicle class and experiment condition. There was 95.8 percent unexplained by the two-way analysis of variance model. The unequal sample size of combinations of vehicle class and experiment conditions in the analysis would be responsible for the small collective effects of vehicle class, experiment conditions and the interaction between them.

Table 4.12 UNIANOVA Test Results

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1553.847a	5	310.769	8.593	.000
	8602.153	1	8602.153	237.863	.000
VehicleClass	18.101	1	18.101	.501	.479
On_Off_Not	757.112	2	378.556	10.468	.000
VehicleClass * On_Off_Not	416.238	2	208.119	5.755	.003
Error	35079.461	970	36.164		
Total	48772.000	976			
Corrected Total	36633.307	975			
a. R Squared = .042 (Adjusted R Squared = .037)					

Table 4.13 and Table 4.14 show the noteworthy findings of in-depth comparison using ANOVA tests. Table 4.13 indicates that for both passenger car and truck classes, the three different experimental conditions had a significant impact on mean speed changes because the significance values are 0.041 for passenger cars and 0.00 for trucks, given a 95% confidence level. Table 4.14 shows the analysis of the three conditions with the different vehicle classes. The values in the Table 4.14 indicate that though the vehicle classes had a significant impact on mean speed reduction under PCMS off and absent (0.002 and 0.034), the impact was not significant when PCMS was on (0.109) given a 95% confidence level.

Table 4.13 Results of Individual Vehicle Classes with Three Condition

Vehicle Class		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Passenger Car	Between Groups	195.666	2	97.833	3.220	.041
	Within Groups	11911.332	392	30.386		
	Total	12106.997	394			
Truck	Between Groups	1175.912	2	587.956	14.668	.000
	Within Groups	23168.129	578	40.083		
	Total	24344.041	580			

Table 4.14 ANOVA Test on Different Conditions by Vehicles Class

Condition		Sum of Squares	df	Mean Square	F	Sig.
No PCMS	Between Groups	161.912	1	161.912	4.468	.036
	Within Groups	6558.394	181	36.234		
	Total	6720.306	182			
PCMS On	Between Groups	106.668	1	106.668	2.576	.109
	Within Groups	14742.382	356	41.411		
	Total	14849.050	357			
PCMS Off	Between Groups	298.865	1	298.865	9.392	.002
	Within Groups	13778.684	433	31.821		
	Total	14077.549	434			

4.5 SUMMARY OF FIELD EXPERIMENT PHASE I

Highway statistics data indicated that 91% of the Kansas public roadway miles are rural, and approximately 97% of the major rural roadways (interstates, principal and minor arterials, and major collectors) are two-lane highways. Preserving, rehabilitating, expending, and enhancing these highways requires having a large number of work zones. To improve safety in work zones, many types of TTC signs have been developed and employed such as PCMS. However, the effectiveness of PCMS in the upstream of work zones has not been quantified. Field experiment Phase I tested the effectiveness of a PCMS on reducing vehicles' speeds in rural two-lane highway work zones under three different conditions: (1) PCMS was on; (2) PCMS was off; and (3) PCMS was absent.

Main results drawn from field experiment Phase I are briefly discussed as follows. First, the data analysis results showed that the PCMS was effective in reducing vehicle speeds in one-lane two-way work zones. Vehicle speeds were reduced by 4.7 mph over an average distance of 500 ft when the PCMS was on. This was an approximate speed reduction of 147 % in comparison to the condition when the PCMS was absent. When the PCMS was off but still visible, the vehicle speeds reduced 3.3 mph over an average distance of 500 ft, a reduction of about 74 % compared to the condition when the PCMS was absent. A mere 1.9 mph speed reduction occurred over an average distance of 500 ft when the PCMS was absent.

Second, after dividing vehicles into passenger car class and truck class, the data analysis results showed that the PCMS was effective in reducing passenger car and truck speeds in one-lane two-way work zones. When the PCMS was on, passenger car speeds were reduced by 4.0 mph and truck speeds were reduced by 5.0 mph over a distance of 500 ft. When the PCMS was off, passenger car speeds were reduced by 2.3 mph and truck speeds were reduced by 4.0 mph over a distance of 500 ft. When the PCMS was absent, passenger car speeds declined by 3.0 mph and truck speeds declined by 1.0 mph over a distance of 500 ft.

Based on the data analysis results, it was concluded that a visible and active PCMS significantly reduces the speed of vehicles (passenger cars and trucks) approaching work zones. A reduction in vehicular speed allows for greater reaction time to avoid crashes and potentially creates a safer environment for drivers and workers in the work zones.

CHAPTER 5: FIELD EXPERIMENT PHASE II

In Chapter 4, it was proved that a visible and active PCMS could be used to reduce the vehicle speeds in the upstream of one-lane two-way rural highway work zones. To maximize the benefits of utilizing a PCMS in rural highway work zones, there is a need to determine the optimal deployment location of a PCMS in the upstream of work zones. Currently, the MUTCD does not specify such a location, traffic engineers have to decide the deployment location based on their experience, which may not be accurate. Thus, determining the optimal deployment location of a PCMS could increase the benefits of utilizing this device.

In field experiment Phase I, a PCMS was placed at 750 ft away from the first TTC sign (W20-1) in the upstream of work zones and mean vehicle speeds were reduced by 4-5 mph. In Chapter 3, the literature review showed that the CMS or PCMS could reduce vehicle speeds within the range from 1 mph to 9 mph. It was possible that the deployment location of a PCMS made a difference on reducing mean vehicle speed. The location where a PCMS is placed in work zones, and the distance between PCMS and standard signing or marking prescribed by the MUTCD, all these factors could affect driver behaviors when they approach work zones. Since it costs considerable money to utilize a PCMS in highway work zones, thus determine the optimal deployment location of the PCMS could also maximize the investment return. The primary objective of field experiment Phase II was to determine the optimal deployment location of a PCMS in the upstream of one-lane two-way rural highway work zones using the vehicle speed profile models.

5.1 EXPERIMENTAL DEVICE AND LAYOUT

5.1.1 Speed Measurement System

In field experiment Phases I, vehicle speeds were measured using SmartSensor radar systems. The SmartSensor system has its own advantages, such as collecting speeds in up to ten lanes. However, there are some drawbacks when applying this system in field experiments including:

- Time and labor consuming. Usually, 25-30 minutes are needed to install and disassemble one set of system with three persons. After installing, 10-20 more minutes are required to adjust the horizontal and vertical orientations so that vehicle speeds could be collected accurately. In total, about 35-50 minutes and three persons are needed for installing and disassembling a single system.
- Sensitive to weather. Since a laptop computer and a real-time human supervision are needed in the field experiments to make sure the data are collected accurately, a light rain could stop the data collecting even construction operations are still going on in the work zones. The smart sensor is mounted on the top of a tripod, the installation makes it easy to tilt the sensor when there is strong wind.

In the field experiment Phase II, the selected rural highway work zones moved 2-3 times everyday. To better accommodate the work zone activity progress, an easy installing-and-disassembling traffic recorder, TRAX Apollyon Counter, was selected for field experiment Phase II. TRAX Apollyon Counter is an automatic traffic recorder manufactured by JAMAR Technologies, Inc. It is designed for ease use, but contains many options and features that could be used for comprehensive traffic data collection. Information on volume, speed, class, and gap can be collected using two pneumatic road tubes and then be converted into traffic data. Figure 5.1 shows one of working counters in the field. A total of seven counters were used in field experiment Phase II. Detailed description of counter layout will be introduced in Section 5.1.2. These 7 counters were named as Sensor 1, 2, 3, 4, 5, 6, and 7 in the field experiment for easy use.

Figure 5.1 TRAX Apollyon Counter in field experiment

As showed in Figure 5.1, two tubes are connected with the counter and are placed perpendicularly to the road; all tubes are fastened by mastic strips. A fixed distance (2 ft) between tubes has to be measured using a ruler. When vehicle tires press on the tubes, the counter detects the air pulse. Therefore, the vehicle speed and classification can be determined by calculating the time gap between vehicle axles. Proper road tube installation is very important for collecting accurate data. There are five steps to install road tubes:

1. Selecting an installation location. In field experiment Phase II, all tubes were installed following the field experimental layout which will be described in the section 5.1.2. The counters were deployed every 250 ft between each other in the upstream of work zones. The Sensor 7 was placed at the same location of the first TTC sign (W20-1: ROAD WORK AHEAD) in the work zones.
2. Determining a layout. A total of 14 tube layouts can be selected in every counter; each of them has its own working environment. The scope of this research was limited to one-lane two-way rural highway work zones, thus, layout L5 was chosen for field experiments Phase II to reduce tube installing time. In this layout, both tubes are extended across the lane to be studied. The tubes should be spaced 2 ft apart with equal length. Figure 5.2 shows L5 layout.
3. Preparing road tubes. After choosing L5 as the layout used in the field experiment, to encompass all types of vehicles and speeds, for a mini tube, a length of 40 to 60 ft is recommended by TRAX Apollyon user's manual. Fourteen 50 ft length mini tubes were used in the field experiments.
4. Preparing the installation tools. Once the layout and mini tubes were selected, having sufficient tools were the key step for a quick and efficient installation on the road. This step includes measuring distance between counters, and preparing mastic strips.

5. Installing the road tubes. Road tubes should be installed exactly perpendicular to the traffic flow. Each counter will be connected to two tubes in the field.

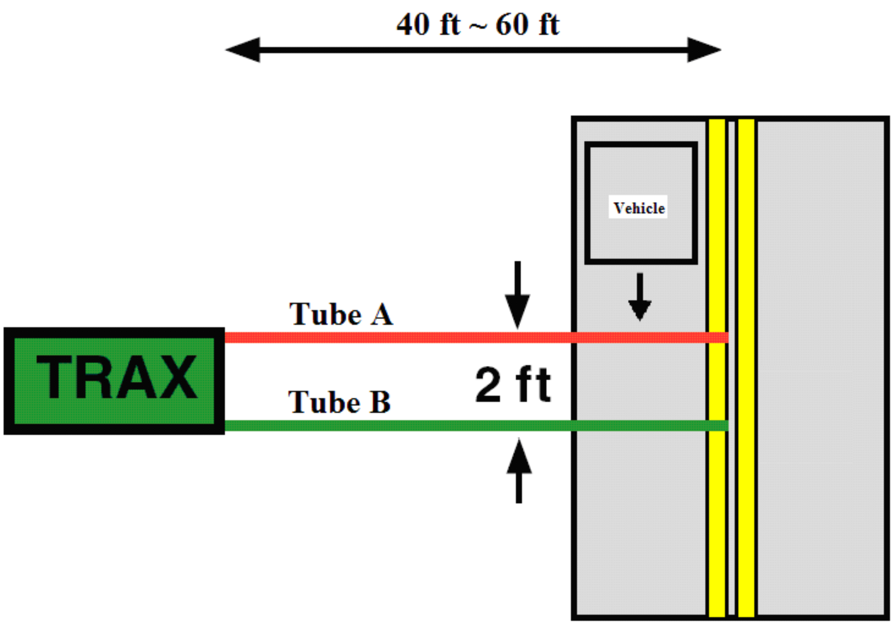


Figure 5.2 L5 Tubes layout

Safety is always the priority when conducting experiments. Reducing working time on the road and keeping alert for upcoming traffics are critical when conducting field experiments. The total installation time needed for one single counter system was about 10 minutes. It included the time for measuring distance between counters, the time for sticking two tubes on the road, and the time for connecting tubes with counters and adjusting counters into working mode. When dissembling the counter system, a total of 4 minutes was needed. Figure 5.3 shows the procedure of tube installation in the field.

1. Preparing mastic strips

2. Fastening tube ends on the road

3. Installing tubes with a tape measure

4. Completing the tube installation

Figure 5.3 TRAX Apollyon Counter installation

5.1.2 Layout of Field Experiments

The primary objective of field experiment Phase II was to determine the optimal deployment location of a PCMS in the upstream of rural highway work zones using the vehicle speed profile models. Theoretically, the speed profile will be exactly accurate if the speed of a vehicle can be recorded every moment along the specific road section. However, it is not feasible to measure the vehicle speed at every second when it approaches a work zone. Thus, seven speed counters were installed at locations where speed changes could be observed in the upstream of work zones.

To determine the distance between counters and record the vehicle speed changes, it is critical to realize that it takes time for drivers to process the traffic information displayed on the highways. When the driver braked for a simple, unexpected decision and action, some of them may take as long as 2.7 seconds to respond (MUTCD). Assuming a vehicle traveling at 65 mph which is the speed limit of rural highways in Kansas, the total distance traveled during the reaction time will be 257 ft. Thus, the 250 ft interval between counters was utilized to record the speed changes in the upstream of work zones. Figure 5.4 shows the layout of field experiment Phase II.

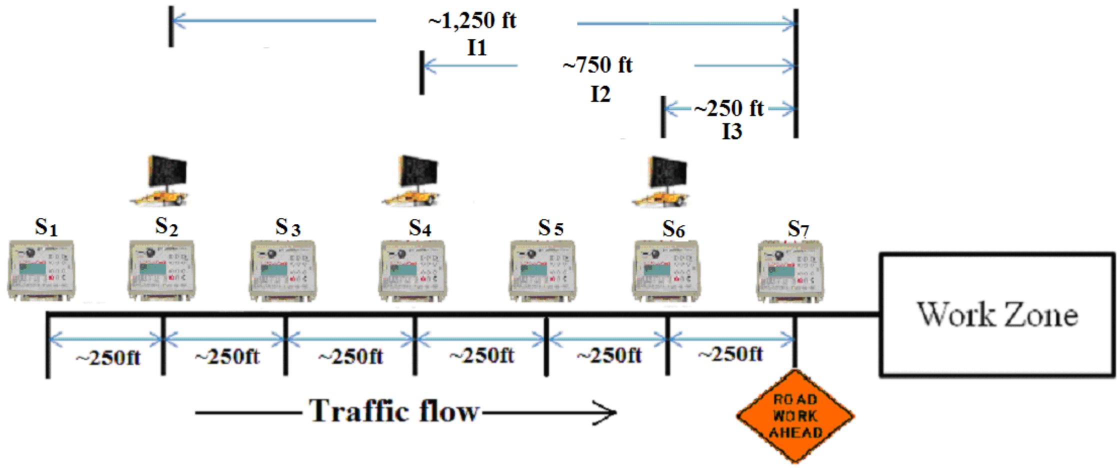


Figure 5.4 Field experiment Phase II layouts

The PCMS was initially placed at three different locations from the start point of a work zone which was the location of the W20-1 sign. These three different locations were: (1) 1,250 ft away from the W20-1, (2) 750 ft away from the W20-1, and 3) 250 ft away from the W20-1. Since the PCMS was placed 750 ft away from the W20-1 in field experiment Phase I, for the consistence reason, the base distance from the PCMS to the W20-1 sign in field experiment Phase II was 750 ft.

In May 2010, the research team conducted the field experiments in a one-lane two-way rural highway work zone located on K-4 as shown in Figure 5.5. The traffic volume on K-4 is 1,120 vehicles per day (vpd) with 165 being trucks. In field experiments, collecting free flow speeds have been proved to be one of key factors to insure the accuracy of data collection. The low traffic volume on K-4 helped the researcher team collect free flow speed data. The highway K-4 had a statutory speed limit of 65 mph. The roadway surfaces were being paved during the construction operations. While construction operations were underway, the two lane highways were reduced to a one-lane two-way work zone that required temporary traffic control signs, flaggers, and a pilot car specified by the MUTCD to coordinate vehicles entering and leaving the work zone. The PCMS used in the field experiments was installed at the upstream of the work zone, in addition to the required temporary traffic control signs, to warn the drivers when they approached the work zone.

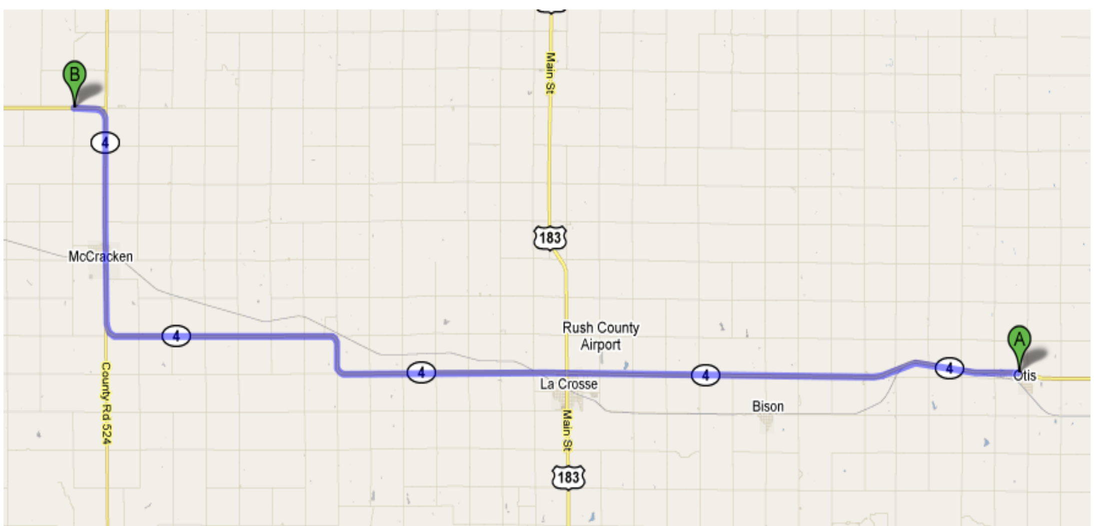


Figure 5.5 Work zone on K-4 in Rush County, Kansas

The dimensions of the PCMS panel were 6.2 ft tall by 11.5 ft wide, it was a little bigger compared with the one used in field experiment Phase I (6.5/10 ft). Figure 5.6 shows the PCMS used in the field experimental site. The messages on the PCMS changed from “WORKZONE/AHEAD/SLOWDOWN” to “FLAGGER/AHD PREP/TO STOP” every three seconds during the experiments. The PCMS was placed on the shoulder of the highway approximately 9-10 ft away from the road. The inside edge of the panel was 3-4 ft away from the road.

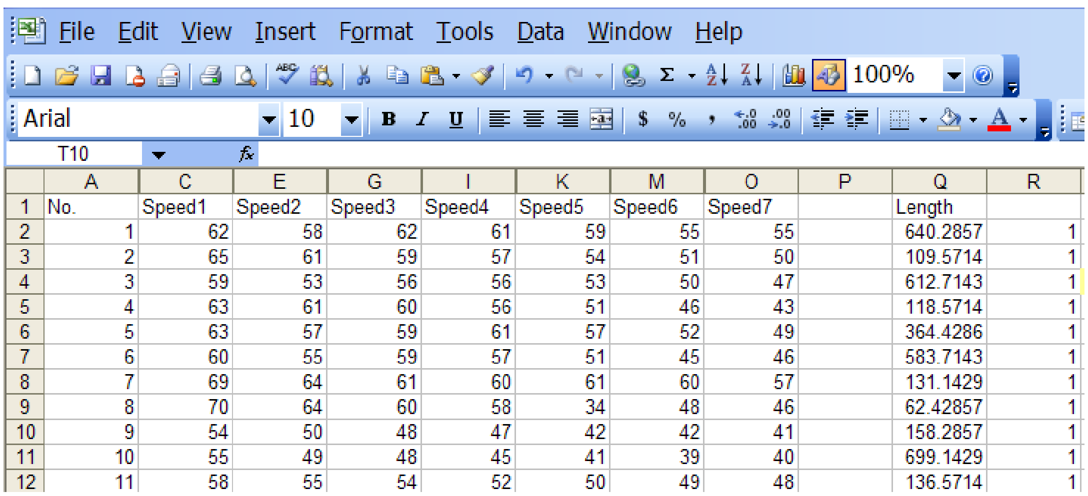
Figure 5.6 Messages displayed on PCMS

5.2 DATA COLLECTION

During field experiment Phase II, the vehicle speeds were collected using the TRAX Apollyon Counter as stated in the last subsection. The data collection procedure was similar to the experiment Phase I, except all seven speed measurements of a vehicle should be collected. External factors, which occasionally interfered with passing vehicles and caused the data to be incorrectly recorded, included the inferences of pedestrians, low-speed farm vehicles, and construction-related vehicles that either had very low speed or whose drivers had been well aware of the upcoming work zone conditions.

The counter systems produced raw data files in a .DMP file format which was used by the specific Jamar software. It was not applicable to conduct data analyses using this format. Thus, the raw data were exported, sorted into datasheet, and went through a screening process for further analyses. The raw data was first thoroughly screened by matching individual vehicle data measurements recorded in all counters. Any vehicle that did not have a corresponding data measurement from all seven counters was discarded. In addition, a data measurement was discarded from the data population if one of vehicle lengths was significant differ from those recorded by other counters.

Figure 5.7 shows a portion of the speed datasheet after sorting all seven speed measurements. The numbers in the first column represent each vehicle collected in the field experiments. Seven speed data measurements were recorded in the following columns. Since there were seven vehicle lengths recorded by the counters, the average length of vehicles was used for data analysis.



	A	C	E	G	I	K	M	O	P	Q	R
1	No.	Speed1	Speed2	Speed3	Speed4	Speed5	Speed6	Speed7		Length	
2	1	62	58	62	61	59	55	55		640.2857	1
3	2	65	61	59	57	54	51	50		109.5714	1
4	3	59	53	56	56	53	50	47		612.7143	1
5	4	63	61	60	56	51	46	43		118.5714	1
6	5	63	57	59	61	57	52	49		364.4286	1
7	6	60	55	59	57	51	45	46		583.7143	1
8	7	69	64	61	60	61	60	57		131.1429	1
9	8	70	64	60	58	34	48	46		62.42857	1
10	9	54	50	48	47	42	42	41		158.2857	1
11	10	55	49	48	45	41	39	40		699.1429	1
12	11	58	55	54	52	50	49	48		136.5714	1

Figure 5.7 Portion of the speed datasheet

A total of 973 vehicle speed data was collected following the time-consuming experiment procedure. Of these, 319 were collected when the PCMS was placed at I_1 location (1,250 ft from the W20-1), 314 were collected when the PCMS was placed at I_2 location (750 ft from the W20-1), and 340 were collected when the PCMS was placed at I_3 location (250 ft from the W20-1).

5.3 DATA ANALYSIS OF EXPERIMENT PHASE II

In Chapter 4, it was proved that using a PCMS could effectively reduce the speeds of vehicles when the PCMS was visible and active. The main task of data analyses in Phase II was to determine the relationship between the PCMS placement locations and the speed reductions using the speed profile models. Knowing this relationship, it is possible to determine the optimal deployment location of a PCMS in the upstream of the work zones.

Tables 5.1, 5.2, and 5.3 show the descriptive statistics of vehicle speeds recorded by each sensor for three PCMS locations. In each table, the number of speed data collected is listed in the second column, followed by the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor location.

Table 5.1 Descriptive Statistics of Vehicle Speeds with PCMS at 1,250 ft

Speed Measurement Location	No. of Data	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	319	25	81	60.4	12.2
Speed at Sensor 2		21	98	64.7	11.7
Speed at Sensor 3		20	81	60.5	10.2
Speed at Sensor 4		24	82	60.6	9.2
Speed at Sensor 5		29	81	60.5	9.4
Speed at Sensor 6		26	79	59.5	9.6
Speed at Sensor 7		21	76	57.4	9.7

Note: STD-Standard Deviation

Table 5.2 Descriptive Statistics of Vehicle Speeds with PCMS at 750 ft

Speed Measurement Location	No. of Data	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	314	23	80	63.0	9.7
Speed at Sensor 2		22	83	62.6	9.5
Speed at Sensor 3		22	79	60.2	9.9
Speed at Sensor 4		22	74	57.7	9.4
Speed at Sensor 5		22	73	55.9	9.4
Speed at Sensor 6		24	77	56.7	10.0
Speed at Sensor 7		19	76	55.2	9.4

Note: STD-Standard Deviation

Table 5.3 Descriptive Statistics of Vehicle Speeds with PCMS at 250 ft

Speed Measurement Location	No. of Data	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	340	25	83	62.1	9.2
Speed at Sensor 2		28	89	65.0	9.5
Speed at Sensor 3		27	86	61.7	9.0
Speed at Sensor 4		27	80	60.5	8.9
Speed at Sensor 5		23	81	60.0	9.9
Speed at Sensor 6		21	80	59.1	10.2
Speed at Sensor 7		24	78	57.1	9.7

Note: STD-Standard Deviation

5.3.1 Comparison of Mean Vehicle Speeds at Sensor 1 and Sensor 7 Locations

There were three different PCMS placement locations (I_1, I_2, and I_3) in the field experiment Phase II, determining if vehicles had equal entering-experimental-site speeds (speeds at Sensor 1 location) and leaving-experimental-site speeds (speeds at Sensor 7) under these three locations was important for the comparison study. Analysis of variance (ANOVA) was used to test the equality of vehicle entering speeds and leaving speeds. Table 5.4 shows the results of ANOVA for vehicle entering speeds at the Sensor 1 location. Since the P-value was 0.006, the vehicles speeds at the Sensor 1 location collected under three PCMS deployment locations were not equal.

Table 5.4 Results of ANOVA for Vehicle Speeds at Sensor 1 Location

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1113.915	2	556.958	5.120	.006
Within Groups	105513.764	970	108.777		
Total	106627.679	972			

Using Levene' test and t-test, three independence comparisons (I_1 vs. I_2, I_1 vs. I_3, and I_2 vs. I_3) were conducted to find detailed entering speeds difference when the PCMS was placed at I_1, I_2, and I_3 locations. Levene's test is an inferential statistic used to assess the equality of variance in different samples (Freund and Wilson 1992). Some statistical procedures assume that variances of the populations from which different samples are drawn are equal. In traffic engineering, the speed variance is an important factor when analyzing crash-related problems. Thus, there is a need to determine whether the speed variances are equal or not from different samples. Levene's test can be used to assess this condition. Using this test, the null hypothesis is that population variances are equal. If the P-value of Levene's test is less than a critical value (0.05), the obtained differences in sample variances are likely to have occurred based on random sampling. Thus, the null hypothesis of equal variances is rejected and it can be concluded that there is a difference between the variances in the population. In Table 5.5, the results of Levene's test for the I_1 vs. I_2 comparison (called Case 1 hereafter) were provided with $p = 0.003$ at $\alpha = 0.05$. Thus, the speed variances were different at the Sensor 1 location when the PCMS was deployed at I_1 (1,250 ft away from the W20-1 sign) and at I_2 (750 ft away from the W20-1 sign).

Table 5.5 Lenvene Test and t-test for Case 1

Independent Samples Test										
		Levene's Test		t-test for Equality of Means with unequal variances						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances not assumed	8.944	.003	-2.957	605.185	.003	-2.592	.877	-4.314	-.870

The t-test was used to compare the mean vehicle speeds at the Sensor 1 location. For the Case 1, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 1)

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Where μ_1 and μ_2 = mean vehicle speed at the Sensor 1 location when the PCMS was placed at I_1 and I_2 locations, respectively. The null hypothesis was interpreted as the mean vehicle speeds at the Sensor 1 location were equal when the PCMS was placed at I_1 and I_2. The alternative hypothesis was interpreted as the mean vehicle speeds at the Sensor 1 location were not equal when the PCMS was placed at I_1 and I_2. A 5% (0.05) level of confidence was used in the t-test. Since the results of Levene's test showed the speed variance between the two populations were not equal, accordingly, the t-test with unequal variances was used for analysis. As shown in Table 5.5, the $p = 0.003 < \alpha$, the null hypothesis was rejected in favor of the alternative. Therefore, there was a statistically significant difference in terms of the mean speeds at the Sensor 1 location when the PCMS was placed at I_1 and I_2. Considering the drivers' sight distance, it was possible that drivers might recognize the PCMS when it was placed at I_1 and reduce the vehicle speed before they hit the Sensor 1 location.

The similar tests were conducted to compare the mean vehicle speeds at the Sensor 1 location when the PCMS was placed at I_1 and I_3 (called Case 2 hereafter). Here I_1 means the PCMS was placed 1,250 ft away from the W20-1 sign, I_3 means the PCMS was placed 250 ft away from the W20-1 sign. Table 5.6 shows the Levene's test and t-test results of Case 2.

Table 5.6 Lenvene Test and t-test for Case 2

Independent Samples Test										
		Levene's Test		t-test for Equality of Means with unequal variances						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances not assumed	11.676	.001	-2.089	589.144	.037	-1.765	.845	-3.425	-.105

In Table 5.6, the results of Levene's test for equality of variances were provided with $p = 0.001$ at $\alpha = 0.05$. Thus, it can be concluded that the population variance were different at the Sensor 1 location when PCMS was placed at I_1 and I_3. Accordingly, the t-test with unequal variances was used for analysis. In the t-test, $p = 0.035 < \alpha$, the null hypothesis was rejected in favor of the alternative. Therefore, there was a statistically significant difference in terms of the mean speeds at the Sensor 1 location when PCMS was placed at I_1 and I_3.

The Levene's test and t-test were conducted to compare the mean vehicle speeds at the Sensor 1 location when the PCMS was placed at I_2 and I_3 (called Case 3 hereafter). Here I_2 means the PCMS was placed 750 ft away from the W20-1 sign, I_3 means the

PCMS was placed 250 ft away from the W20-1 sign. The Levene's test and t-test results are shown in Table 5.7.

Table 5.7 Lenvene Test and t-test for Case 3

Independent Samples Test										
		Levene's Test		t-test for Equality of Means with equal variances						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances assumed	.071	.790	1.119	652	.264	.827	.739	-.625	2.279

As shown in Table 5.7, the results of Levene's test for equality of variances were provided with $p = 0.79$ at $\alpha = 0.05$. Thus, the speed variances were not different at the Sensor 1 location when the PCMS was placed at I_2 and I_3. Accordingly, the t-test with equal variances was used for analysis. In the t-test, the $p = 0.264 > \alpha$, thus the null hypothesis was accepted. Therefore, there was no statistically significant difference in terms of the mean speeds at the Sensor 1 location when PCMS was placed at I_2 and I_3.

When vehicles reached the location of the first TTC sign (W20-1 sign), the same location of Sensor 7, the measured speeds were named work-zone-entering speeds or leaving-experimental-site speeds. Determining if work-zone-entering speeds equal or not under three PCMS placement locations was critical in comparison with mean speeds at the Sensor 1 location. Same as before, ANOVA was used to test the equality of population means. Table 5.8 shows the results of ANOVA for vehicle work-zone-entering speeds at the Sensor 7 location. Since the P-value was 0.006, the vehicles speeds at the Sensor 7 location under three PCMS deployment locations were not equal.

Table 5.8 Results of ANOVA for Vehicle Speeds at Sensor 7 Location

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	953.684	2	476.842	5.127	.006
Within Groups	90216.053	970	93.006		
Total	91169.737	972			

Using Levene' test and t-test, three independence comparisons (I_1 vs. I_2, I_1 vs. I_3, and I_2 vs. I_3) were conducted to find the detailed difference of work-zone-entering speeds. In Table 5.9, the results of Levene's test for the I_1 vs. I_2 comparison (called Case 4 hereafter) were provided with p = 0.974 at α = 0.05. Thus, the speed variances were not different at the Sensor 7 location when the PCMS was placed at I_1 (1,250 ft from the W20-1 sign) and at I_2 (750 ft from the W20-1 sign).

Table 5.9 Levene Test and t-test for Case 4

Independent Samples Test										
		Levene's Test		t-test for Equality of Means with equal variances						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor7	Equal variances assumed	.001	.974	2.939	631	.003	2.242	.763	.744	3.740

The t-test was used to compare the mean vehicle speeds at the Sensor 7 location. For the Case 4, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 4)

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Where μ_1 and μ_2 = mean vehicle speed at the Sensor 7 location when the PCMS was placed at I_1 and I_2, respectively. The null hypothesis was interpreted as the mean vehicle speeds at the Sensor 7 location were equal when the PCMS was placed at I_1 and I_2. The alternative hypothesis was interpreted as the mean vehicle speeds at the Sensor 7 location were not equal when the PCMS was placed at I_1 and I_2. A 5% (0.05) level of confidence was used in the t-test. Since the results of Levene's test showed the speed variances between the two populations were equal, accordingly, the t-test with equal variances was used for analysis. As shown in Table 5.9, the $p = 0.003 < \alpha$, the null hypothesis was rejected in favor of the alternative. Therefore, there was a statistically significant difference in terms of the mean speeds at the Sensor 7 location when the PCMS was placed at I_1 and I_2.

The similar tests were conducted to compare the mean vehicle speeds at Sensor 7 location when the PCMS was placed at I_1 and I_3 (called Case 5 hereafter). Here I_1 means the PCMS was placed 1,250 ft away from the W20-1 sign, I_3 means the PCMS was placed 250 ft away from the W20-1 sign. Table 5.10 shows the Levene's test and t-test results.

Table 5.10 Levene Test and t-test for Case 5

Independent Samples Test										
		Levene's Test		t-test for Equality of Means with equal variances						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor7	Equal variances assumed	.005	.945	.351	657	.726	.266	.759	-1.224	1.756

As shown in Table 5.10, the result of Levene's test for equality of variances was $p = 0.945$ at $\alpha = 0.05$. Thus, it can be concluded that the speed variance were not different at the Sensor 7 location when the PCMS was placed at I_1 and I_3. Accordingly, the t-test with equal variances was used for analysis. In the t-test, p = 0.726 > α, thus the null hypothesis was accepted. Therefore, there was no statistically significant difference in terms of the mean speeds at the Sensor 7 location when the PCMS was placed at I_1 and I_3.

Levene's test and t-test were conducted to compare the mean vehicle speeds at the Sensor 7 location when the PCMS was placed at I_2 and I_3 (called Case 6 hereafter). Here I_2 means the PCMS was placed 750 ft away from the W20-1 sign, I_3 means the PCMS was placed 250 ft away from the W20-1 sign. The results of Levene's test and t-test are shown in Table 5.11.

Table 5.11 Levene Test and t-test for Case 6

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor7	Equal variances assumed	.011	.917	-2.630	652	.009	-1.976	.751	-3.451	-.501

As shown in Table 5.11, the results of Levene's test for equality of variances were provided with p = 0.917 at α = 0.05. Thus, the population variances were not different at the Sensor 7 location when the PCMS was placed at I_2 and I_3. Accordingly, the t-test with equal variances was used for analysis. In the t-test, the p = 0.009 < α, thus the null hypothesis was rejected in favor of the alternative. Therefore, there was a statistically significant difference in terms of the mean speeds at the Sensor 7 location when PCMS was placed at I_2 and I_3.

In Table 5.12, the results of t-test were summarized for vehicle speeds at the locations of Sensors 1 and 7. When the PCMS was placed at locations of I_1 and I_3, the mean speeds of entering experimental site for I_1 and I_3 conditions were significantly different and the mean speeds of leaving experimental site for these two conditions were not different at 95% confidence level. This meant that deploying the PCMS at the I_3 location the mean vehicle speed had larger reduction than the one that deploying the PCMS at the I_1 location when vehicles passed the experimental site. For the similar reason, when placing the PCMS at the I_2 location, the mean vehicle speed had larger reduction than the one that the PCMS was placed at the I_3 location. Though the mean vehicle speeds at the Sensor 1 and the Sensor 7 locations were significantly different when the PCMS was placed at I_1 and I_2, the mean speed reduced 7.8 mph when the PCMS was placed at I_2 and only 3 mph reduction occurred when the PCMS was placed at I_1. In summary, deploying the PCMS at the I_2 location can mostly reduce the mean vehicle speed.

Table 5.12 Results of t-test for Mean Speeds at the Locations of Sensors 1 and 7

PCMS Location	Mean Speeds at Sensor 1 Location	Mean Speeds at Sensor 7 Location	Comparison Results
I_1 vs. I_2	Significantly Different	Significantly Different	N/A
I_1 vs. I_3	Significantly Different	No Different	Deploying PCMS at I_3 had larger speed reduction than PCMS at I_1
I_2 vs. I_3	No Different	Significantly Different	Deploying PCMS at I_2 had larger speed reduction than PCMS at I_3

5.3.2 Development of Vehicle Speed Profile Models

The vehicle speed profile models were developed using the vehicle speeds at the locations of seven sensors. In the SPSS software, the command of Curve Estimation in Regression was selected to generate the models that could be used to fit the speed profiles.

There are Linear, Quadratic, Compound, Growth, Logarithmic, Cubic, S, Exponential, Inverse, Power, and Logistic models which are available in the Curve Estimation. To determine the best fit model, the distance of Sensor 1 (X coordinate) was set up at one foot instead of zero feet to avoid zero in models like "Inverse, S, Logarithmic and Power." After changing Sensor 1's X coordinate, the R square value indicated that the Cubic model was the best fit for three models of different PCMS locations as shown in Table 5.13. The speed profile curves and mean speeds at the locations of seven counters were presented in Figures 5.8, 5.9, and 5.10.

Table 5.13 Speed Profile Models for Three PCMS Locations

PCMS Placement Location	Speed Profile Models
I1 (1,250ft to W20-1)	Y=57.826+0.003x+0.000005615x^2-0.00000000389x^3
I2 (750ft to W20-1)	Y=55.616-0.003x+0.00001168x^2-0.0000000042x^3
I3 (250ft to W20-1)	Y=57.55+0.001x+0.000008626x^2-0.000000004734x^3

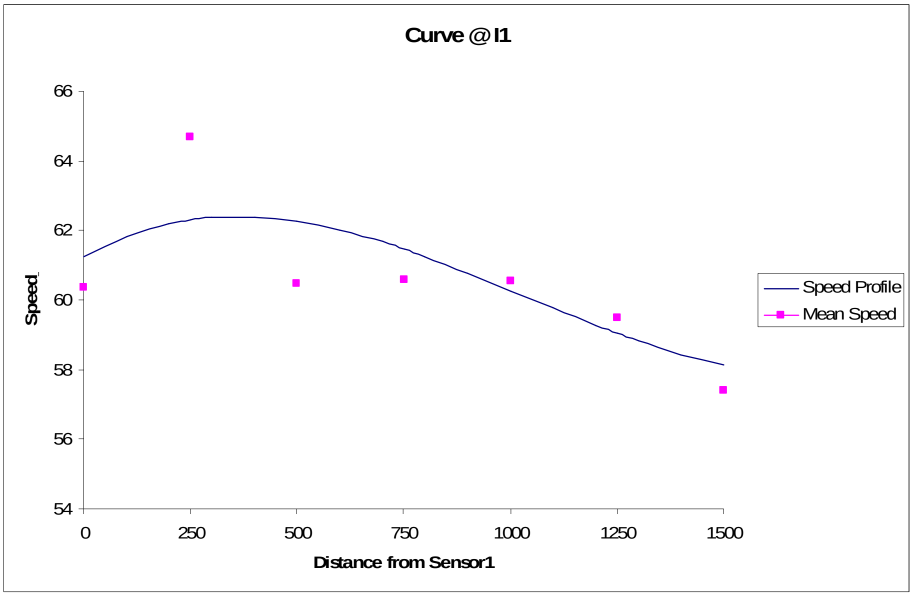


Figure 5.8 Speed profile curve for PCMS at 1,250 ft

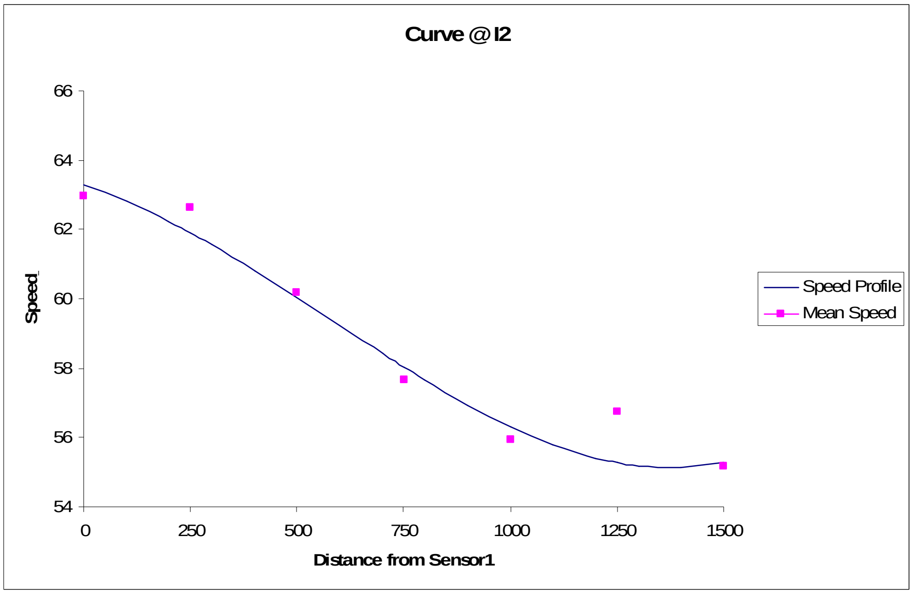


Figure 5.9 Speed profile curve for PCMS at 750 ft

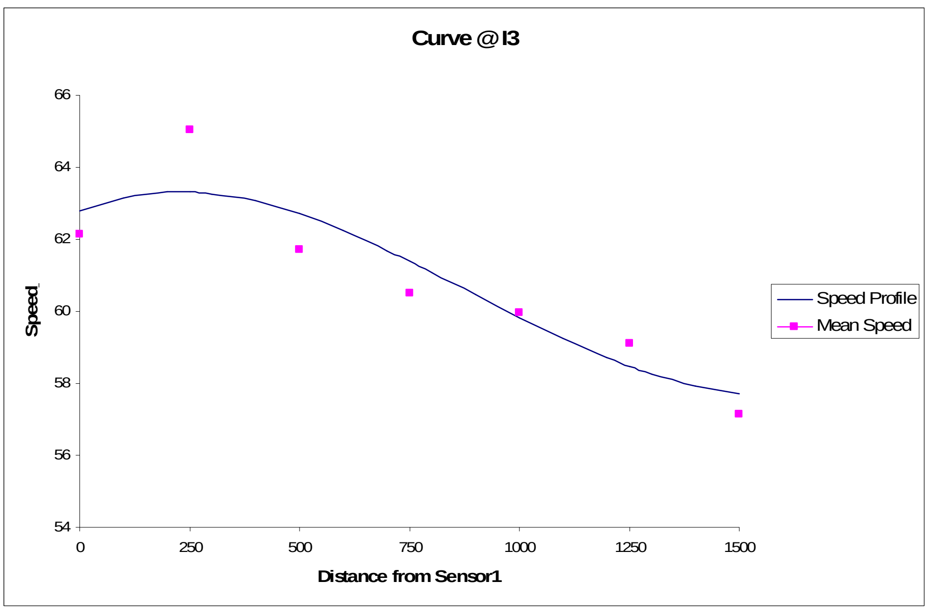


Figure 5.10 Speed profile curve for PCMS at 250 ft

Figure 5.11 shows three speed curves corresponding to three PCMS deployment locations. As it indicated, when the PCMS was placed at 750 ft away from the W20-1 sign, the mean speeds of vehicles reduced the most and the speed curve declined smoothly. When the PCMS was placed at 1,250 ft or 250 ft away from the W20-1 sign, the speed curves ascended first and then declined. The up-down of the speed curve indicates the increasing variance of speeds, which should be avoided in the traffic flow. In other words, if a PCMS is not placed properly in the upstream of a work zone, it may have negative impact on vehicle safety due to unexpected speed changes.

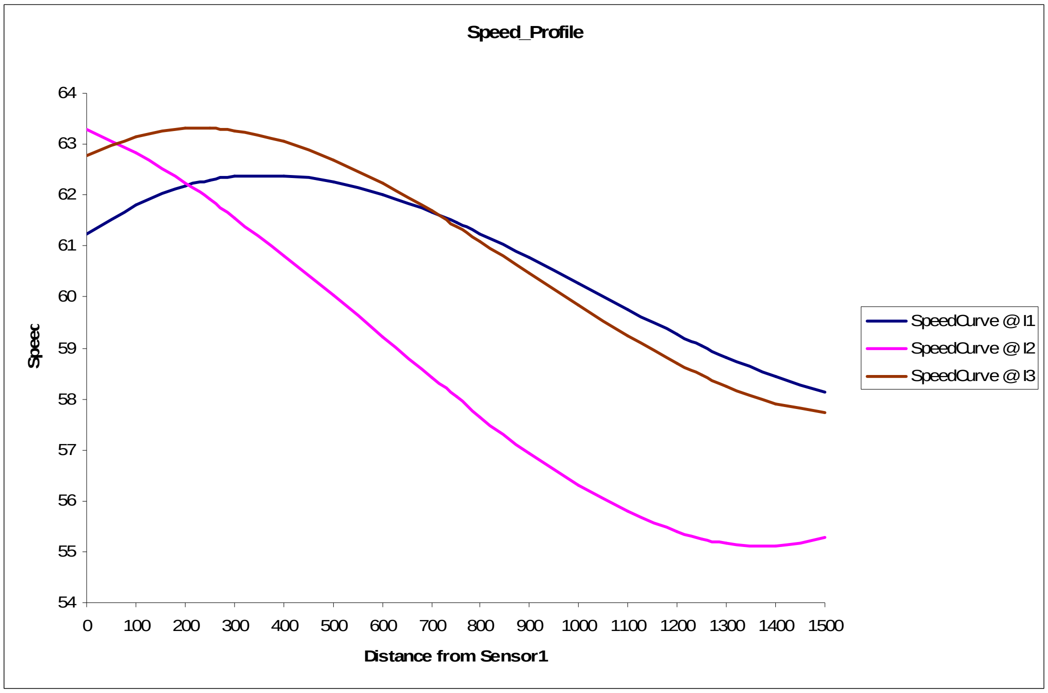


Figure 5.11 Speed profile curves for three Cases

To determine the optimal deployment location of a PCMS, the measured vehicle speeds at the location of Sensor 7 were first used to develop the regression model that could be used to describe the relationship between the PCMS placement location and the speed of entering a work zone. The objective was to have the lowest vehicle speed at the entrance of a work zone (lowest speed at the location of the W20-1 sign). Figure 5.12 shows that a Quadratic model can be used to best describe the relationship. The model can be expressed as:

$$Y=0.000006x^2-0.0069x+57.145$$

Based on the equation above, the optimal deployment location of a PCMS in the upstream of work zones is 575 ft away from the W20-1 sign. The vehicle speed at W20-1 location is 55.2 mph if the PCMS was placed at 575 ft away from the W20-1 sign.

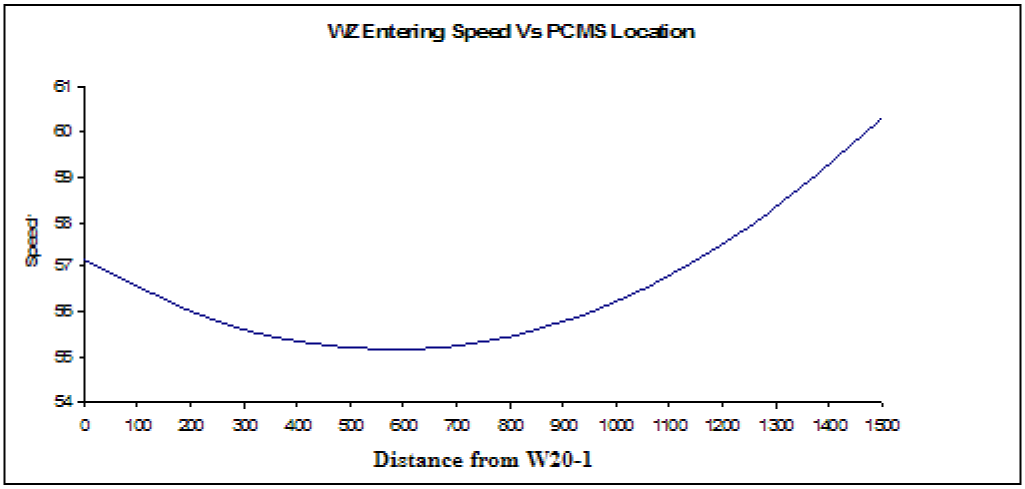


Figure 5.12 Relationship between PCMS placement location and Mean Speed at W20-1

As a comparison, the vehicle speeds at the location of Sensor 7, calculated using the three speed profile models (shown in Table 5.13), were utilized to determine the optimal deployment location of a PCMS with the same objective. The Quadratic model that can be used to best describe the relationship is as follows.

$$Y=0.000007x^2-0.0085x+57.145$$

Based on this equation, the optimal deployment location of a PCMS in the upstream of work zones is 607 ft away from the W20-1 sign. The vehicle speed at W20-1 location is 55.1 mph if the PCMS was placed at 607 ft away from the W20-1 sign.

5.4 SUMMARY OF FIELD EXPERIMENT PHASE II

The results of data analyses confirmed that the PCMS was effective in reducing mean vehicle speeds in the upstream of a work zone. When the PCMS was placed 1,250 ft away from the W20-1 sign, the vehicle mean speed was reduced by 3 mph over the distance of 1,500 feet. When the PCMS was placed 750 ft away from the W20-1 sign, the vehicle mean speed was reduced by 8 mph over the distance of 1,500 feet. When the PCMS was placed 250 ft away from the W20-1 sign, a 5 mph speed reduction occurred over the distance of 1,500 feet. Using the ANOVA, Levene's test, and t-test, it was proved that when a PCMS was placed at the I_2 location (750 ft away from the first TTC sign: W20-1), the mean vehicle speed had the largest reduction compared with those when a PCMS was placed at the I_1 and I_3 locations. In other words, the deployment location of a PCMS will have a significant impact on vehicle speed reduction. Thus, it is important to determine the optimal PCMS deployment location in order to maximize the benefits of using this device.

To develop the vehicle speed profile models in the upstream of the work zone, curve estimation in the statistic software SPSS was used. Based on the results of the data analyses, it was concluded that the cubic models could be used to represent the vehicle speed profiles in the upstream of a work zone. From the speed profile models, it was observed that if a PCMS was not placed properly in the upstream of a work zone, it would have negative impact on vehicle safety due to unexpected speed changes.

In addition, based on the speed profile models, when the PCMS was placed at 607 ft away from the first TTC sign (W20-1 sign), the PCMS would be most effectively on reducing vehicle speeds in the upstream of the one-lane two-way rural highway work zones. Using the speed measurements at the location of Sensor 7, it was determined that the optimal PCMS deployment location was 575 ft away from the first TTC sign. Since the vehicle speed at the entrance of work zones calculated under these two conditions were equal, it is possible that the optimal PCMS deployment location is not a single point, rather is a range. To determine this range, additional field experiments are needed, which will be described in the next chapter.

CHAPTER 6: FIELD EXPERIMENT PHASE III

Results of data analyses in Chapter 5 indicated that the optimal deployment location of a PCMS in the upstream of rural highway work zones could be a range, not an exact single point. The conclusion was reached based on the fact that the optimal deployment location could be derived using two different sets of data: 1) the speeds collected at the Sensor 7 location, and 2) the speeds determined using the profile models. To verify this conclusion and determine the range of optimal deployment location, field experiment Phase III was conducted from September 21st to October 1st in 2010. In Phase III, the field experiments were conducted by deploying the PCMS at three locations which were 400 ft, 575 ft, and 750 ft away from the first TTC sign (W20-1 sign) in the upstream of a one-lane two-way rural highway work zone. The same speed measurement devices, TRAX Apollyon Traffic Counter sensors, were used again. A detailed description of the TRAX Apollyon Traffic Counter was provided in Section 5.1.1. The installation and adjustment of seven sensors followed the same procedure as stated in Section 5.1.1.

6.1 FIELD EXPERIMENT LAYOUT

The objectives of field experiment Phase III were to define the optimal deployment range of a PCMS in the upstream of one-lane two-way rural highway work zones and determine driver's opinions on the utilization of a PCMS in the work zones using the survey method. Same as the experimental layout of field experiment Phase II, seven speed sensors were used in the field experiment and distributed every 250 ft in the upstream of a work zone. Figure 6.1 shows the layout of field experiment Phase III.

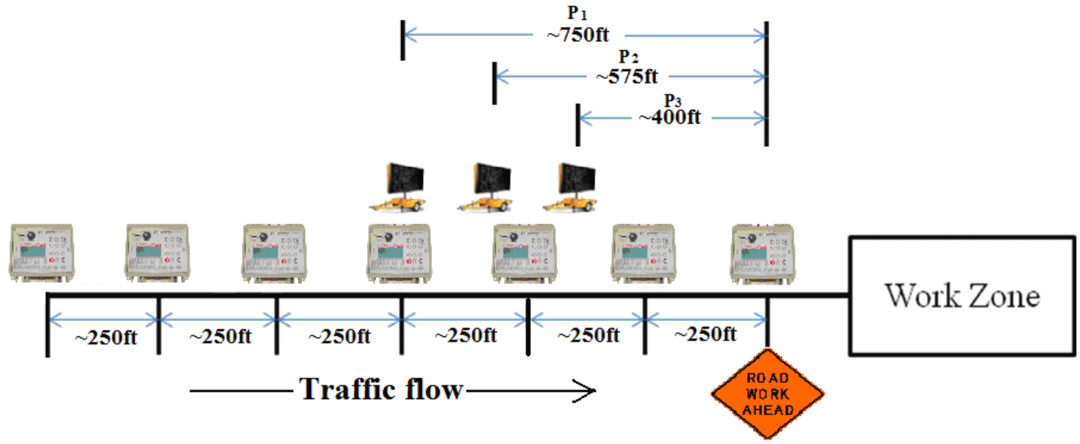


Figure 6.1 Layout of field experiment Phase III

In the field experiment Phase III, the PCMS was placed at three different locations including: (1) P_1: 750 ft away from the W20-1 sign, (2) P_2: 575 ft away from the W20-1 sign, and 3) P_3: 400 ft away from the W20-1 sign. The PCMS locations covered the possible optimal deployment range of a PCMS, plus these locations were easy to be identified in the field.

In September and October 2010, the experiments were conducted in the upstream of a one-lane two-way rural highway work zone located on the US-36 as shown in Figure 6.2. The traffic volume on US-36 was 3,550 vehicles per day (vpd) with 590 being trucks. The US-36 had a statutory speed limit of 65 mph. The roadway surfaces were being paved during the construction operations. While construction operations were underway, the two lane highway was reduced to a one-lane two-way work zone that required temporary traffic control signs, flaggers, and a pilot car specified by the MUTCD to coordinate vehicles entering and leaving the work zone. The PCMS used in the field experiments was installed in the upstream of the work zone, in addition to the required temporary traffic control signs, to warn the drivers when they approached the work zone.

The PCMS used in Phase III was the same one as in Phase II as shown in Figure 6.3. The messages displayed on the PCMS were also the same. They were "WORKZONE/AHEAD/SLOWDOWN" and "FLAGGER/AHD PREP/TO STOP." These two phases changed every three seconds during the experiment. The PCMS was placed on the shoulder of the highway approximately 9 - 10 ft from the road. The inside edge of the panel was 3 - 4 ft away from the road.

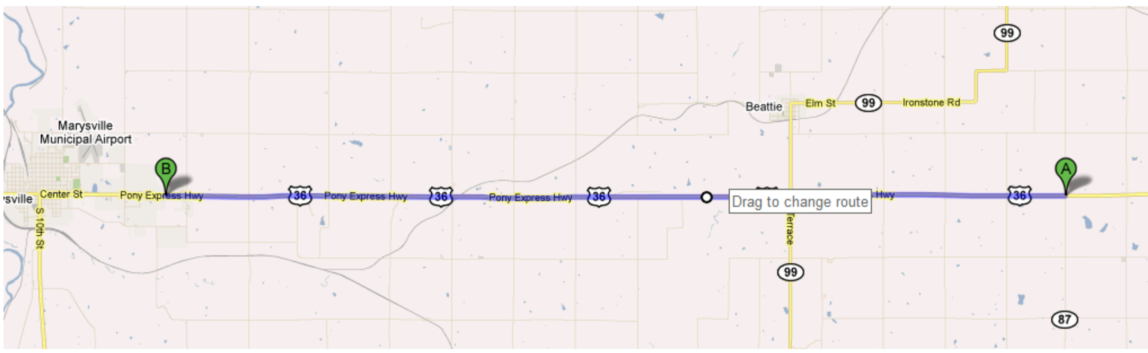


Figure 6.2 Work zone on US-36

Figure 6.3 Messages displayed on PCMS in field experiment Phase III

6.2 DATA COLLECTION

The vehicle speed data were collected and stored by the TRAX Apollyon Traffic Counter sensors in field experiment Phase III. Same as previous experiments, a speed datum was kept for further analysis if all seven speed measurements of a vehicle were collected. External factors, which occasionally interfered with passing vehicles and caused the data to be incorrectly recorded, included the interferences of pedestrians, low-speed farm vehicles, and construction-related vehicles that either had very low speed or whose drivers had been well aware of the upcoming work zone conditions. These factors were taken into consideration in the data collection process.

The raw data .DMP files collected in the field experiment were exported, sorted into datasheet, and gone through a screening process. Any single vehicle datum that did not have corresponding speed measurements from all seven counters was discarded. In addition, a datum measurement was discarded from the data population if one of vehicle length measurement was significantly different from other measurements.

A total of 3,265 vehicle speed data was collected following the time-consuming experimental procedure. Of these, 1,144 vehicle speed data were collected when the PCMS was placed at P_1 location (750 ft); 1,125 were collected when the PCMS was placed at P_2 location (575 ft); and 996 were collected when the PCMS was placed at P_3 location (400 ft).

6.3 DATA ANALYSIS OF FIELD EXPERIMENT PHASE III

In the analysis, the data set of each PCMS location was divided into two parts: one was for model development and the other one was for model validation. When dividing data set into two parts, simple random sampling was used via a statistical software program. Simple random sampling, or random sampling without replacement, is a sampling design in which n distinct units are selected from the N units in the population in such a way that every possible combination of n units is equally likely to be the sample selected (Thompson 2002). This sampling was performed by the command of random sample of cases in the SPSS statistical software. Table 6.1 shows the number of data for model development and validation when the PCMS was placed at three different locations. When the PCMS was placed at 750 ft away from the W20-1 sign, it was named Situation 1 hereafter. Situations 2 and 3 (called hereafter) mean that the PCMS was placed at 575 ft and 400 ft away from the W20-1 sign, respectively.

Table 6.1 Speed Data Sampling in Field Experiment Phase III

PCMS Location	Data for Model Development	Data for Model Validation	Total
PCMS at 750ft	585	559	1,144
PCMS at 575ft	569	556	1,125
PCMS at 400ft	496	500	996

6.3.1 Model Development and Validation for Situation One

When the PCMS was placed at 750 ft upstream of the W20-1 sign, 585 speed data were sorted and used for the speed profile model development. The key point for profile model development was to find a curve which could be used to best describe speeds when vehicles were approaching the work zone.

The vehicle speed profile models were developed by using the vehicle speed data at seven sensor locations. Using the SPSS software program, regression analyses using Curve Estimation were conducted to determine the model that could best represent the collected data. There are Linear, Quadratic, Compound, Growth, Logarithmic, Cubic, S, Exponential, Inverse, Power, and Logistic models which can be chosen in the Curve Estimation. To find the best fit model, the X coordinate of Sensor 1 location was set as one foot to avoid zeros in the Inverse, S, Logarithmic and Power models. According to the R square value of each model, the Cubic model was the best fit. Table 6.2 shows the results of model development. The Cubic model of Situation 1 is:

$$Y = 60.749 - 0.002x - 1.713e^{-6}x^2 + 1.776e^{-10}x^3$$

X: Distance between a vehicle location and the Sensor 1 location ($1 \leq x \leq 1{,}500$ ft)

Y: Vehicle speed

Table 6.2 Speed Profile Models when PCMS Placed at 750 ft

Model Summary and Parameter Estimates									
Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.965	136.291	1	5	.000	61.177	-.004		
Logarithmic	.508	5.161	1	5	.072	61.668	-.659		
Inverse	.305	2.196	1	5	.198	57.426	3.485		
Quadratic	.980	104.363	2	4	.000	60.766	-.002	-1.313E-6	
Cubic	.981	52.320	3	3	.004	60.749	-.002	-1.713E-6	1.776E-10
Compound	.960	121.033	1	5	.000	61.243	1.000		
Power	.495	4.904	1	5	.078	61.725	-.011		
S	.294	2.086	1	5	.208	4.050	.060		
Growth	.960	121.033	1	5	.000	4.115	-7.515E-5		
Exponential	.960	121.033	1	5	.000	61.243	-7.515E-5		

It is important to validate the developed model before utilizing it in engineering practice. According to the developed equation, the vehicle speed could be calculated using the distance between a vehicle location and the Sensor 1 location. Table 6.3 shows the vehicle speeds at the locations of seven sensors in the upstream of the work zone.

Table 6.3 Vehicle Speeds Determined Using Cubic Model for Situation 1

Sensor Location (ft)	Calculated Speed at Sensor Location (mph)
1	60.7
250	60.1
500	59.3
750	58.2
1,000	56.9
1,250	55.2
1,500	53.3

The validation process was to compare the mean speeds at the locations of seven sensors (measured speeds) with the speeds derived from the developed model (calculated speeds). The mean speed at each sensor location was determined using 559 field measurements that were allocated for model validation as shown in Table 6.1. A t-test was used to determine if the measured speeds were equal to the calculated speeds. In addition to the t-test, the absolute value of speed difference between the measured speed and calculated speed and the percentage of difference were calculated for additional comparisons.

In the t-test, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Situation 1)

$$H_0: \mu_m = \mu_c$$

$$H_1: \mu_m \neq \mu_c$$

Where μ_m means the <u>m</u>easured mean speed and μ_c means the <u>c</u>alculated speed at the Sensor 1 location. The null hypothesis was interpreted as the measured mean speed at the Sensor 1 location was equal to the calculated speed. The alternative hypothesis was interpreted as the measured mean speed was not equal to the calculated speed.

As shown in Table 6.4, the P-value of the t-test was 0.849 for speed comparison at the Sensor 1 location, so it was concluded that it was failed to reject the null hypothesis because the P-value was larger than 0.05. The same tests were conducted for speeds at the other six sensor locations. Only one measured speed at the Sensor 7 location was different from the calculated speed. The difference was about 1 mph, or 2% between measured speed and the calculated speed. From the engineering practice stand point of view, the difference was minor and could be ignored. Therefore, it was concluded that the calculated speeds were accurate enough to represent the measured speeds for Situation 1. Figure 6.4 shows the curve developed from the speed profile model and the measured mean speeds.

Table 6.4 Comparison of Measured Speeds with Calculated Speeds for Situation one

Location	Measured Mean Speed (mph)	Calculated Mean Speed (mph)	Mean Speed difference (mph)	Mean Speed difference (%)	t	P-value
Sensor1	60.8	60.7	0.056	0.09	0.191	0.849
Sensor2	59.6	60.1	-0.500	0.83	-1.72	0.085
Sensor3	59.1	59.3	-0.193	0.33	-0.62	0.534
Sensor4	58.4	58.2	0.150	0.26	0.443	0.658
Sensor5	57.2	56.9	0.158	0.28	0.491	0.624
Sensor6	55.1	55.2	-0.108	0.20	-0.35	0.73
Sensor7	54.5	53.3	1.084	2.00	3.437	0.001

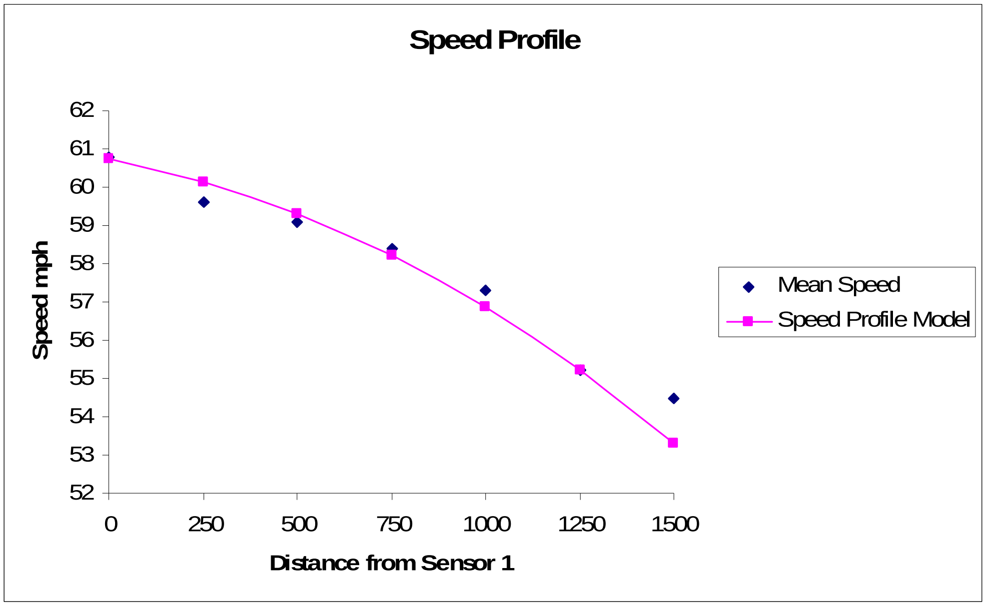


Figure 6.4 Speed profile curve for PCMS at 750 ft

6.3.2 Model Development and Validation for Situation Two

When the PCMS was placed at 575 ft upstream of the W20-1 sign, 569 speed data were sorted and used for the speed profile model development and 556 field measurements were used for the model validation as shown in Table 6.1.

A similar model selection process was conducted to develop the speed profile model for Situation 2. According to the R square value of each model, the Cubic model was the best fit. The Cubic model of Situation 2 is:

$$Y = 62.278 - 0.01x + 7.384e^{-6}x^2 - 3.736e^{-9}x^3$$

X: Distance between a vehicle location and the Sensor 1 location ($1 \leq x \leq 1{,}500$ ft)

Y: Vehicle speed

Table 6.5 shows the vehicle speeds at the locations of seven sensors in the upstream of the work zone.

Table 6.5 Vehicle Speeds Determined Using Cubic Model for Situation 2

Sensor Location (ft)	Calculated Speed at Sensor Location (mph)
1	62.3
250	60.2
500	58.7
750	57.4
1,000	55.9
1,250	54.0
1,500	51.3

The similar model validation process was conducted for Situation 2. Table 6.6 shows the P-values of t-tests and the percentages of mean speed differences for Situation 2. There were three measured speeds, which were collected at the Sensors 2, 4, and 6 locations, were different from the calculated speeds. The speed differences at these locations were 1.8 (2.9%), 1.2 (2.0%), and 1.6 mph (3.0%), respectively. Though the measured speeds were not equal to the calculated speeds at these three locations, the differences were small from the engineering practice stand point of view, thus the calculated speeds could be used to represent the measured speeds. Figure 6.5 shows the curve developed from the speed profile model and the measured mean speeds.

Table 6.6 Comparison of Measured Speeds with Calculated Speeds for Situation 2

Location	Measured Mean Speed (mph)	Calculated Mean Speed (mph)	Mean Speed difference (mph)	Mean Speed difference (%)	t	P-value
Sensor1	62.7	62.3	0.376	0.60	1.355	0.176
Sensor2	58.5	60.2	-1.774	2.90	-6.10	0.000
Sensor3	59.0	58.7	0.302	0.50	0.977	0.329
Sensor4	58.5	57.4	1.163	2.03	3.477	0.001
Sensor5	56.5	55.9	0.598	1.07	1.768	0.078
Sensor6	52.5	54.0	-1.617	3.00	-5.20	0.000
Sensor7	52.0	51.3	0.524	1.02	1.703	0.089

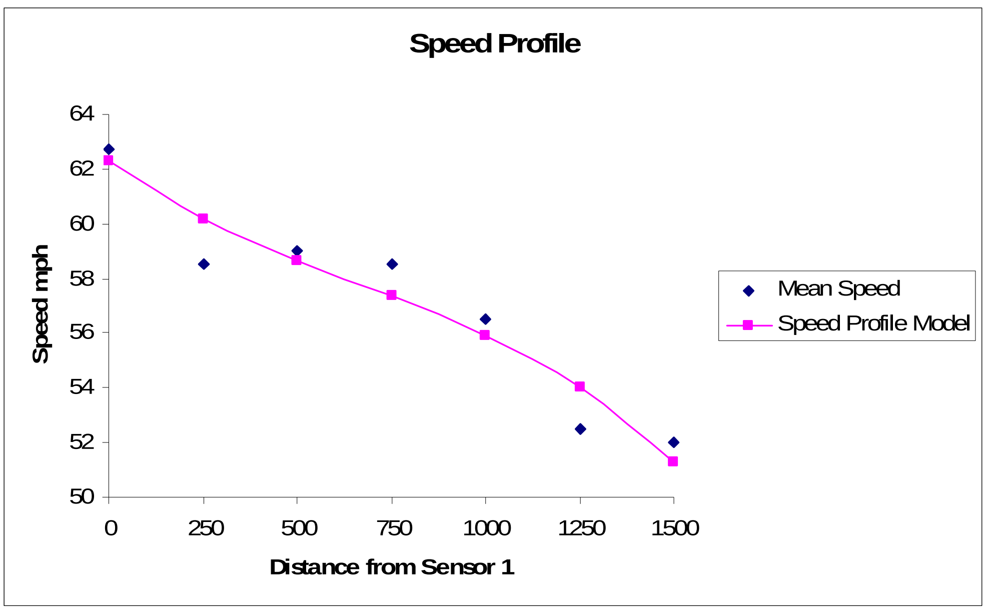


Figure 6.5 Speed profile curve for PCMS at 575 ft

6.3.3 Model Development and Validation for Situation Three

When the PCMS was placed at 400 ft upstream of the W20-1 sign, 496 speed data were sorted and used for the speed profile model development and 500 field measurements were used for the model validation as shown in Table 6.1.

A similar model selection process was conducted to develop the speed profile model for Situation 3. According to the R square value of each model, the Cubic model was the best fit. The Cubic model of Situation 3 is:

$$Y = 61.075 - 0.003x - 5.328e^{-7}x^2 - 8.884e^{-10}x^3$$

X: Distance between a vehicle location and the Sensor 1 location ($1 \le x \le 1{,}500$ ft)

Y: Vehicle speed

Table 6.7 shows the vehicle speeds at the locations of seven sensors in the upstream of the work zone.

Table 6.7 Vehicle Speeds Determined Using Cubic Model for Situation 3

Sensor Location (ft)	Calculated Speed at Sensor Location (mph)
1	61.1
250	60.3
500	59.3
750	58.2
1,000	56.7
1,250	54.8
1,500	52.4

The similar model validation process was conducted for Situation 3. Table 6.8 shows the P-values of t-tests and the percentages of mean speed differences for Situation 3. There were three measured speeds, which were collected at the Sensors 2, 5, and 7 locations, were different from the calculated speeds. The speed differences at these locations were 0.8 (1.3%), 1.0 (1.7%), and 1.0 mph (1.9%), respectively. Though the measured speeds were not equal to the calculated speeds at Sensor 2, 5, and 7 locations, the differences were small from the engineering practice stand point of view, thus the speed profile curve could be used to represent the measured speeds. Figure 6.6 shows the curve developed from the speed profile model and the measured mean speeds.

Table 6.8 Comparison of Measured Speeds with Calculated Speeds for Situation 3

Location	Measured Mean Speed (mph)	Calculated Mean Speed (mph)	Mean Speed difference (mph)	Mean Speed difference (%)	t	P-value
Sensor1	61.4	61.1	0.288	0.47	0.975	0.33
Sensor2	59.5	60.3	-0.778	1.29	-2.60	0.013
Sensor3	59.1	59.3	-0.216	0.36	-0.65	0.515
Sensor4	58.7	58.2	0.478	0.82	1.305	0.192
Sensor5	57.6	56.7	0.986	1.74	2.625	0.009
Sensor6	54.2	54.8	-0.516	0.94	-1.53	0.127
Sensor7	53.4	52.4	1.010	1.93	3.028	0.003

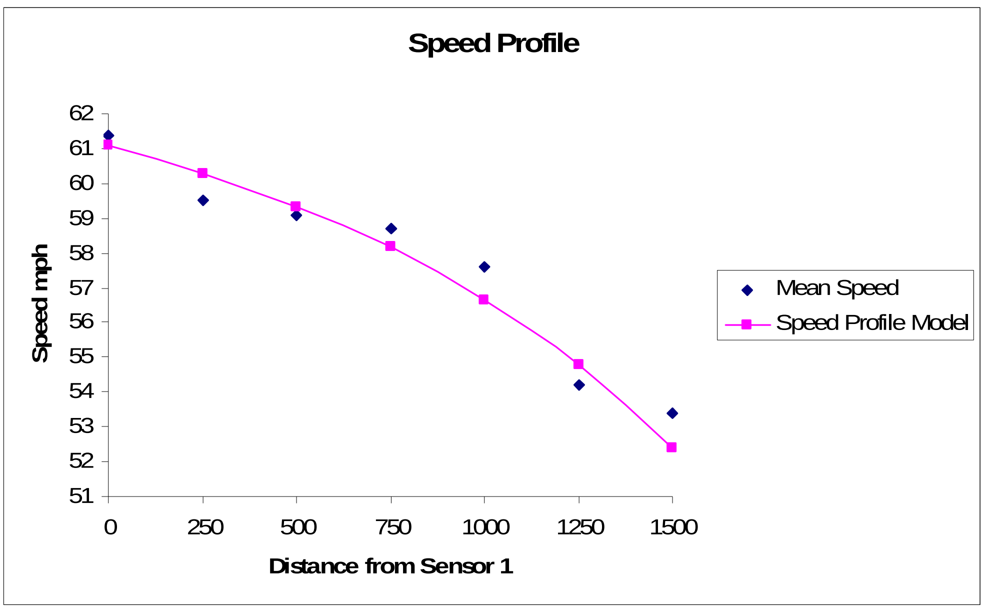


Figure 6.6 Speed profile curve for PCMS at 400 ft

6.3.4 Determining Optimal Deployment Range of a PCMS

Figure 6.7 shows three speed curves corresponding to three PCMS deployment locations. When the PCMS was placed at 575 ft away from the W20-1 sign, the entering-work-zone speed (speed at Sensor 7 location) had the smallest value. Compared with

Figure 5.11 in Chapter 5, it was observed that when the PCMS was placed at 750 ft, 575 ft, and 400 ft, the mean vehicle speeds declined when drivers were approaching work zones without the up-down variation which occurred when the PCMS was placed at 1,250 ft and 250 ft. In other words, the curves indicated that the drivers slowed down consistently and smoothly when the PCMS was placed at 750 ft, 575 ft, and 400 ft away from the W20-1 sign compared with the curves when the PCMS was placed at 1,250 and 250 ft away from the W20-1 sign.

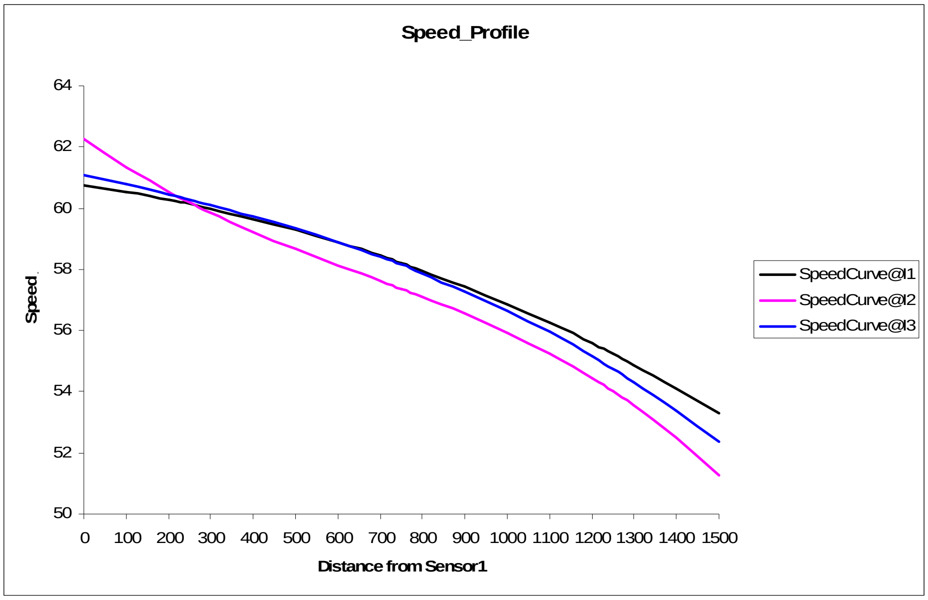


Figure 6.7 Speed profile curves for three situations

To determine the optimal deployment range of a PCMS, the measured speeds at the location of Sensor 7 were first used to develop the regression model that could be used to describe the relationship between the PCMS placement location and the speed of entering a work zone. The objective was to have the lowest vehicle speed at the entrance of a work zone (lowest speed at the location of the W20-1 sign or the location of Sensor 7). Figure 6.8 shows that a Quadratic model can be used to best describe the relationship. The model can be expressed as:

$$Y=0.00006x^2-0.0636x+69.133$$

Based on the equation above, the optimal deployment location of a PCMS in the upstream of work zones is 530 ft away from the W20-1 sign with the speed of 52.3 mph at the entrance of a work zone.

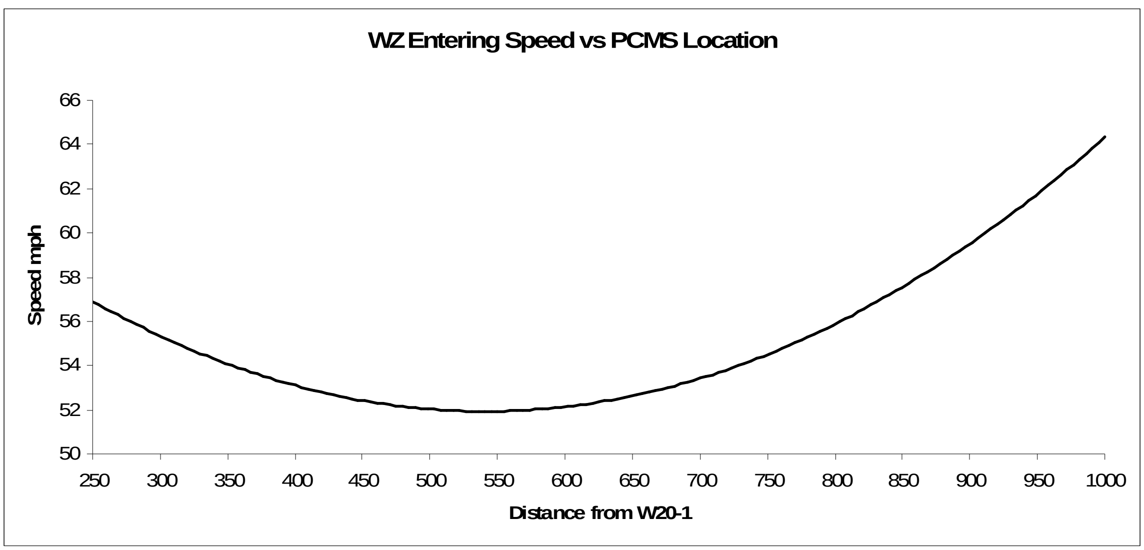


Figure 6.8 Relationship between PCMS placement location and mean speed at W20-1

As a comparison, the calculated speeds using the three speed profile models at the location of Sensor 7 were utilized to determine the optimal deployment location of a

PCMS with the same objective. The Quadratic model that can be used to best describe the relationship is as follows.

$$Y=0.00005x^2-0.0556x+66.555$$

Based on this equation, the optimal deployment location of a PCMS in the upstream of work zones is 556 ft away from the W20-1 sign with the speed of 51.1 mph at the entrance of a work zone.

Table 6.9 shows the summary of the optimal deployment locations of a PCMS in the upstream of a work zone based on the results of field experiment Phases II and III. It was observed that the optimal deployment locations changed from 575 ft to 530 ft away from the W20-1 sign when using measured speeds, and from 607 ft to 556 ft away from the W20-1 sign when using calculated speeds. The overlap of these two ranges, 556 ft to 575 ft away from the W20-1 sign, was define as the optimal deployment range of a PCMS in the upstream of one-lane two-way rural highway work zones. Deploying a PCMS in this range will result in the smallest work zone entering speed (speed at the W20-1 sign) and vehicles speeds will be reduced smoothly in the upstream of work zones.

Table 6.9 Summary of Optimal Deployment Locations from Field Experiments

Optimal Deployment Location of a PCMS in Upstream of Work Zone	Field Experiment Phase II	Field Experiment Phase III
Based on Measured Mean Speed at Sensor 7 Location	575 ft away from W20-1	530 ft away from W20-1
Based on Calculated Mean Speed at Sensor 7 Location	607 ft away from W20-1	556 ft away from W20-1

6.4 DRIVER SURVEY

Conveying effective traffic control messages via a PCMS to motorists will reduce confusion, non compliance, or misinterpretation. Thus, to better understand drivers' reactions to a PCMS installed in the upstream of rural highway work zones, a driver survey was conducted in field experiment Phase III with a total of 352 participants. The survey contained information about driver/vehicle characteristics, drivers' perceptions of messages displayed on the PCMS, reactions taken after seeing the messages, the effectiveness of a PCMS as a traffic control device, and acceptance of utilization of a PCMS in the upstream of rural highway work zones.

6.4.1 Development of Survey Questionnaire

The questionnaire was designed in an effort to thoroughly gather the drivers' interpretation of the messages displayed on the PCMS and their opinions on the potential implementation of a PCMS through short questions that could be finished within a short period of time (about three minutes). An example of the survey form was included in Appendix I and questions included in the survey are described as follows.

Question 1: Did you see the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?

This was a simple yes/no question which included two pictures that showed the two phases of a working PCMS. If a surveyed driver provided "No" as the answer, the survey would be terminated. If the driver answered "Yes," the survey would be continued with the rest of the questions.

Question 2: Did you understand the messages displayed on the PCMS?

This yes/no question was designed to gather the drivers' interpretation of the warning messages. Since the second phase of the messages on the PCMS was "FLAGGER/ AHD PREP/ TO STOP," this question would also be helpful to determine the drivers' understanding about abbreviations used in the messages.

Questions 3: What actions did you take after you saw the PCMS?

This question was included so that drivers' actions, in response to the warning sign, could be collected for comparison with their interpretations of the PCMS. The available answers for this question included: 1) Slow down, 2) Look for more information, 3) Do nothing, and 4) Take other action. A driver could describe his/her actions if the answer was "Take other action."

Question 4: Did you think that the PCMS drew your attention more to the work zone traffic condition?

This yes/no question was designed to verify if the PCMS could more effectively alert drivers when they approached the work zones.

Question 5: Do you prefer the use of a PCMS to alert drivers about the upcoming work zones in addition to the existing sign?

This simple yes/no question was designed to obtain the drivers' recommendation on the potential implementation of the PCMS in the upstream of rural highway work zones. The answers to this question would indicate if the surveyed drivers would like to see the PCMS implemented in rural highway work zones.

Other than the above questions, the survey form also included such information as date, time, weather condition, vehicle type, and gender of the surveyed drivers. The types of the vehicles include passenger cars, minivans, pickups, campers or RVs, sport utility vehicles (SUVs), all – terrain vehicles, and trucks. The trucks included single large trucks, truck and trailers, tractor-trailers, and buses.

6.4.2 Survey Data Collection

The driver survey was conducted at the location where the flagger stopped the vehicles. One of the major advantages of surveying work zone drivers at this location was that the drivers had to stop and wait for their turn to pass work zones (the typical waiting time was 10 – 15 minutes). Thus, surveys could be conducted at the waiting period without interrupting traffic. This resulted in a higher percentage of successful surveys and more thoughtful and thorough opinions.

The surveys were conducted from 9:00 a.m. to 5:00 p.m. on weekdays when work zones were under construction. Though the construction operations in the work zone started at 5:30 a.m., the survey was conducted after 9:00 a.m. to avoid the sun glare which could affect drivers' visions. Figure 6.9 shows a research assistant conducting a survey.

Figure 6.9 Conducting a survey in a work zone

A driver survey could be finished within three minutes. In the work zone, vehicles typically had to wait for approximately ten to fifteen minutes in a traffic queue in front of the flagger. Thus, about 5-6 drivers could finish the questionnaire before leaving the flagger location. A total of 352 motorists were asked to participate in the survey. Three of them did not respond to the survey. 349 drivers completed the questionnaires; all of them were the drivers of the vehicles.

6.4.3 Analysis of Survey Results

6.4.3.1 Driver Profile

The distribution of the vehicle types is given in Figure 6.10. There were 291 passenger cars, which count for 83 percent of total number of vehicles, and 58 trucks which count for 17 percent of the total number of vehicles.

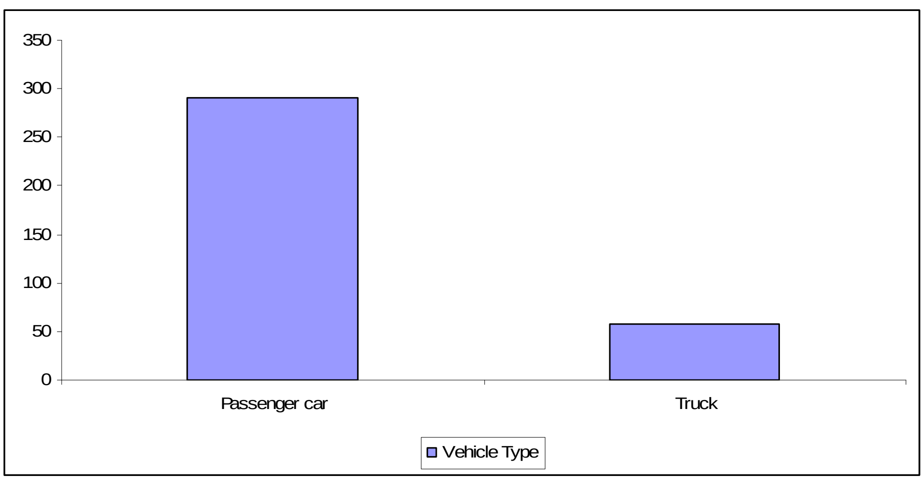


Figure 6.10 Number of passengers cars and trucks

Demographic information about the drivers surveyed indicated that 237 were male, which counts for 68 percent, and 112 female which counts for 32 percent. Figure 6.11 shows the number of male and female drivers.

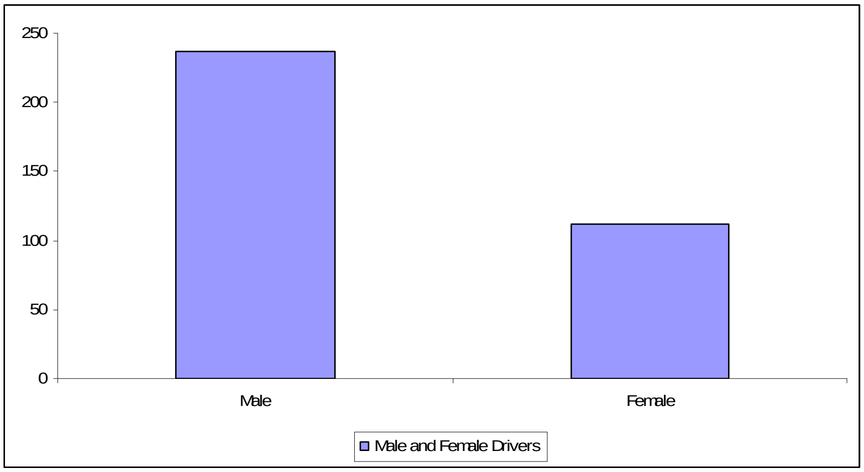


Figure 6.11 Number of male and female drivers

6.4.3.2 Results of Survey

Results of survey questionnaire are presented as follows.

Question 1: Did you see the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?

The analysis of the responses to the first question showed that the PCMS successfully captured the attention of 96% (335 out of 349) of the surveyed drivers. Only 4% (14 out of 349) of the surveyed drivers didn’t see the PCMS when they were approaching the work zone, as shown in Figure 6.12. Factors which were observed in the experimental site and might cause a small proportion of drivers who claimed not seeing the PCMS included:

1: Sun glare. The surveys were conducted after 9:00 a.m., the sunlight could be very bright especially in early afternoons on the sunny days. In addition, during late afternoons when bright sunlight was directly against the driving direction, a driver could not easily recognize the PCMS and the messages displayed on it.

2: Vehicles came from an intersection which was located between the PCMS and the flagger. Since the placement of the PCMS was in the upstream of the work zone, there were some intersections between the PCMS location and the flagger location, thus, drivers could not see the PCMS if they entered the work zone from these intersections.

3: Unwillingness to participate. Some drivers might not want to participate in the survey, and thus, simply responded “no” to discontinue the survey.

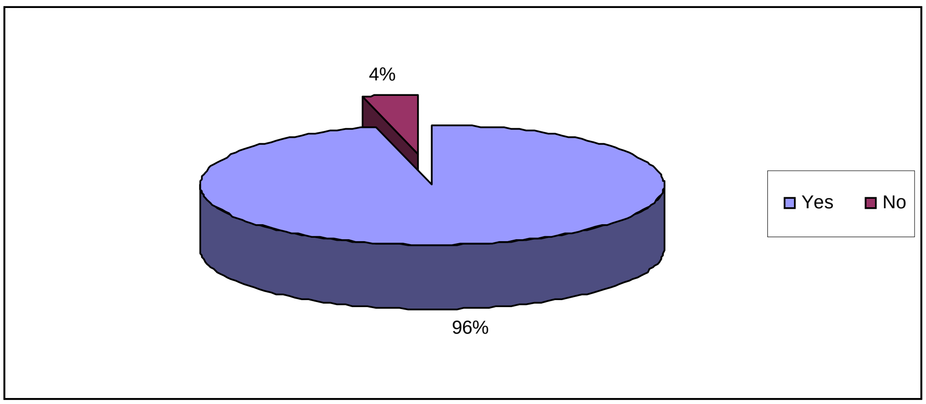


Figure 6.12 Responses of the first survey question

Question 2: Did you understand the messages displayed on the PCMS?

As mentioned in the feedback of question 1, 14 drivers claimed not seeing the PCMS when they were entering the work zone, thus, they were not given the rest of the questions. The following analyses of the survey were based on the feedbacks of 335 drivers who responded “yes” to the first question.

The analysis results of the responses to the second question showed that 99% (333 out of 335) of the surveyed drivers understood the messages displayed on the PCMS as shown in Figure 6.13. Only 1% (2 out of 335) of the surveyed drivers did not understand what the messages meant. This outcome indicated that the message displayed in abbreviations, “FLAGGER/ AHD PREP/ TO STOP,” was understandable by most of drivers.

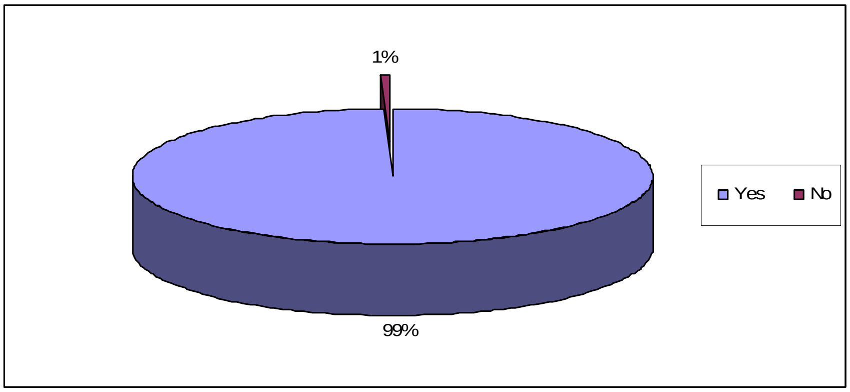


Figure 6.13 Responses of the second survey question

Question 3: What actions did you take after you saw the PCMS?

This question had four answers including: 1) Slow down, 2) Look for more information, 3) Do nothing, and 4) Take other action. The question was designed to understand what reactions drivers would take after they saw the PCMS in the work zone. Drivers might give multiple answers during the survey. For example, some drivers said that they slowed down and looked for more information at the same time.

Table 6.10 shows the response frequencies, in which 85% of surveyed drivers slowed down when they saw the PCMS in the upstream of the work zone. In addition, 12% of the drivers were looking for more information when they slowed down. There were two drivers who responded that they slowed down and took other actions. However, they did not describe what kind of action they took. 3% of drivers just looked for more information when they saw the PCMS, and there were two drivers who did nothing when they saw the PCMS. In total, there were 97% of drivers who slowed down after seeing the PCMS in the upstream of the work zone.

Table 6.10 Response Frequencies of the Third Question

Response	Frequency			Percent (%)		
	Male	Female	Total	Male	Female	Total
Slow down	198	86	284	59	26	85
Look for more information	8	0	8	2	0	2
Do nothing	2	0	2	1	0	1
Slow down and Look for more information	23	16	39	7	5	12
Slow down and Take other actions	2	0	2	1	0	1
Take other actions	0	0	0	0	0	0

Question 4: Did you think that the PCMS drew your attention more to the work zone traffic condition?

This question was designed to measure the effectiveness of a PCMS in alerting drivers of the irregular traffic conditions. The analysis of the responses to this question showed that 96% (322 out of 335) of the surveyed drivers agreed that the PCMS drew their attention more to the work zone traffic conditions; 4% (13 out of 335) of the drivers did not think the PCMS drew their attention more to work zone conditions.

Question 5: Do you prefer the use of a PCMS to alert drivers about the upcoming work zones in addition to the existing sign?

The survey questionnaire included this question to directly obtain the drivers' recommendation on the implementation of a PCMS in rural highway work zones. The survey results on this question would be a meaningful indication of the acceptance of the PCMS by work zone travelers. Results of data analysis indicated that 94% (315 out of 335) of the drivers recommended using the PCMS in addition to the existing traffic signs.

6% (20 out of 335) of the drivers did not prefer the application of the PCMS in rural highway work zones.

6.4.3.3 Correlation Analysis

In the questionnaire in addition to the five survey questions, the types of vehicles were coded as one for passenger cars and two for trucks; and the drivers' gender was numbered one for male and two for female. The Pearson Correlation Coefficient could be used in measuring the correlation between two variables when one is at least interval and the other is dichotomous or when both are dichotomous. For survey questions two, four, and five, their answers (variables), yes or no, are dichotomous. Thus, the Phi Coefficient was used to determine the correlation. The Phi Coefficient is the name given to a case of the Pearson Coefficient when both variables are dichotomous.

Phi Coefficients were computed to determine whether there was a relationship between the gender of the drivers and the answers to questions two, four, and five and the relationship between vehicle types and answers to questions two, four, and five. The results of the correlation analyses presented in Table 6.11 show that neither gender nor vehicle type had significant correlation to the responses of questions two, four, and five. In general, the results indicated that the gender of the driver did not affect the drivers' understanding of the messages; both male and female drivers thought the PCMS drew their attention more to the work zone conditions and preferred the PCMS application in rural highway work zones. Driving different types of vehicles did not make a difference on drivers' understanding of messages; in addition, both truck and passenger car drivers thought the PCMS drew their attention more to the work zone conditions and preferred its application in rural highway work zones.

Table 6.11 Correlation Analysis on Vehicle Types and Driver Gender

		Phi Coefficient	Significant Correlate?
Vehicle Types	Question 2	-0.035	No
	Question 4	-0.009	No
	Question 5	0.054	No
Driver Gender	Question 2	-0.051	No
	Question 4	-0.032	No
	Question 5	-0.057	No

Some drivers gave multiple answers to question three during the survey, thus, the Point Biserial Correlation Coefficient was used to test the correlation between gender/vehicle type and actions taken. The results of the correlation analyses are presented in Table 6.12.

Table 6.12 Point Biserial Correlation Analysis for Question 3

		Point Biserial Correlation Coefficient	Significant Correlate?
Question 3	Gender	-0.110	Yes
	Vehicle Type	0.072	No

Table 6.12 shows that the gender of the drivers had an effect on what actions were taken after seeing the PCMS. As shown in Table 6.10, there were eight male drivers who chose “look for more information” without slowing down after they saw PCMS, and 23 male drivers looked for more information and slowed down at the same time. There were two male drivers who did nothing after they saw the PCMS and other two male drivers took other actions when they slowed down. All female drivers slowed down after seeing the PCMS. Among them, 16 female drivers looked for more information at the same time. No female drivers looked for more information without slowing down. The analysis

results indicated that the PCMS had more effective impact on female drivers on reducing vehicle speeds than on male drivers.

6.5 SUMMARY OF FIELD EXPERIMENT PHASE III

Chapter 5 pointed out that the optimal deployment location of a PCMS in the upstream of one-lane two-way rural highway work zones could be a range rather than a single point. Field experiment Phase III was conducted to verify this conclusion and determine the range of optimal deployment location of a PCMS. Three speed profile models were developed based on the speed measurements at seven sensor locations using the curve estimation. The speed profile models quantify the relationship between the vehicle speed and the vehicle location and depict the changes of vehicle speeds in the upstream of work zones.

Each speed profile model was validated by t-tests and percentage of difference. The model validation showed that though two models could not provide vehicle speed estimation at three sensor locations with the statistically same accuracy as the mean of field measurements by the sensors, the differences were minor from the engineering practice stand point of view. The speed profile curves could depict the trends of vehicle speed changes when they were approaching the work zone. When the PCMS was placed 750 ft away from the W20-1 sign, the vehicle mean speed was reduced by 7.4 mph over the distance of 1,500 ft. When the PCMS was placed 575 ft away from the W20-1 sign, the vehicle mean speed was reduced by 11 mph over the distance of 1,500 ft. When the PCMS was placed 400 ft away from the W20-1 sign, an 8.7 mph speed reduction occurred over the 1,500 ft distance.

Based on the speed profile models, when the PCMS was placed at 556 ft away from the first TTC sign (W20-1 sign), the PCMS would be most effective on reducing vehicle speeds to 51.1 mph before entering the work zone. Using the speed measurements at the location of Sensor 7, it was determined that the optimal PCMS deployment location was 530 ft away from the W20-1 sign, where the vehicle speed was 52.3 mph before entering the work zone. When comparing the results of field experiment Phase II and Phase III, it was found that the optimal deployment location changed from 575 ft to 530 ft (the first range) away from the W20-1 sign when using speed measurements at the location of Sensor 7, and from 607 ft to 556 ft (the second range) away from the W20-1 sign when using speed profile models. Based on the results of experiment Phase II and III, the optimal deployment range of a PCMS was determined which was from 556 ft to 575 ft away from the W20-1 sign. This range was the overlap of the first range determined by the field measurement data and the second range determined by the vehicle speed profiles.

Results of the survey showed that a majority of drivers were able to recognize the messages displayed on the PCMS. 97% of the drivers slowed down when they saw the PCMS; 14% of the drivers looked for more information; 96% of drivers thought the PCMS drew their attention more to the work zone traffic conditions. Consequently, a majority of the drivers (94%) would recommend the implementation of a PCMS in the upstream of the work zone in addition to the existing traffic signs.

When it comes to the influence of gender of drivers on actions which were taken after seeing the PCMS, the results showed that the PCMS had a better effect on female drivers who all slowed down their vehicles. There were 16 female drivers who looked for more information when they slowed down. In contrast, there were eight male drivers who looked for more information after they saw the PCMS, and two male drivers did nothing. Driving different types of vehicles did not make a difference on drivers' understanding of messages; in addition, both truck and passenger car drivers thought the PCMS drew their attention more to the work zone conditions and preferred its application in rural highway work zones.

CHAPTER 7: SPEED REDUCTION COMPARISON BETWEEN PASSENGER CARS AND TRUCKS

In Chapter 3, the literature review on truck safety pointed out that truck related crashes contribute to a significant percentage of motor vehicle crashes in the United States, which often result in fatalities and injuries. The amount of truck miles traveled is dramatically increasing with the growing rate of freight movement. Regarding truck safety in the work zones, many studies indicated that there was a significant increase in crash severity when a truck crash occurred in the work zones. Therefore, it requires more attention to the safety of trucks in the work zones.

To mitigate the prominent high crash rate and severity of truck-related crashes in the work zones, the effectiveness of a PCMS was tested on reducing passenger car and truck speeds in the upstream of work zones as stated in Chapter 4. The results of field experiment Phase I showed that when a visible and active PCMS was deployed in the upstream of work zones, passenger car speeds were reduced by 4.0 mph and truck speeds were reduced by 5.0 mph over a distance of 500 ft. In field experiments Phase II and III, the optimal deployment range of a PCMS in the upstream of work zones was determined using the speed measurements and vehicle speed profile models. However, these models were developed by using all vehicles which did not reflect the difference between passenger cars and trucks when they were approaching the work zones. Because of the characteristics of trucks, it is difficult for truck drivers to maneuver large trucks smoothly on roadways. Due to the difference of driving behaviors between passenger car drivers and truck drivers, it might be necessary that the separate speed profile models were required to understand more in depth the effectiveness of a PCMS on reducing speeds of passenger cars and trucks in the upstream of rural highway work zones.

7.1 OBJECTIVES AND SCOPE

The primary objectives of this chapter were 1) to develop the passenger car speed profile model in the upstream of a rural highway work zone, 2) to develop the truck speed profile model in the upstream of a rural highway work zone, 3) to determine if there were differences between the speed reductions of passenger cars and trucks when they were approaching the work zones.

In September and October 2010, when field experiment Phase III was conducted in the upstream of a one-lane two-way rural highway work zone located on Highway US-36, data of passenger cars and trucks were collected using seven speed sensors. Since there were seven sensors used in the experiments, the vehicle length was determined by the average of the seven length measurements. If the average length of a vehicle was larger than 200 inches, then the vehicle was classified as a truck. A total of 1,144 vehicle speed data was collected when the PCMS was placed at 750 ft away from the first TTC sign (W20-1 sign). Among them, 799 were passenger cars and 345 were trucks. When the PCMS was placed at 575 ft away from the W20-1 sign, there were 761 passenger cars and 364 trucks. When the PCMS was placed at 400 ft away from the W20-1 sign, speed data of 652 passenger cars and 344 trucks were collected. Table 7.1 shows the list of data collected when the PCMS was placed at three different locations.

Table 7.1 Speed Data by Vehicle Types at Different PCMS Locations

PCMS Location	No. of Passenger Cars	No. of Trucks	Total
PCMS at 750ft	799	345	1,144
PCMS at 575ft	761	364	1,125
PCMS at 400ft	652	344	996

7.2 DATA ANALYSIS

The major tasks that needed to be accomplished were the development of the passenger car and truck speed profile models when the PCMS was placed at three different locations in the upstream of the work zone and the comparison between the passenger car speed reduction and the truck speed reduction. When the PCMS was placed at 750 ft away from the W20-1 sign, it was named Situation 1 as it was in Chapter 6. Situations 2 and 3 mean that the PCMS was placed at 575 ft and 400 ft away from the W20-1 sign, respectively.

7.2.1 Passenger Car and Truck Speed Profile Model for Situation One

7.2.1.1 Passenger Car Speed Profile Model for Situation One

When the PCMS was placed at 750 ft upstream of the W20-1 sign, 799 passenger car speed data were collected in the field experiments as shown in Table 7.1. Table 7.2 shows the descriptive statistics of passenger car speeds recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor are listed.

Table 7.2 Descriptive Statistics of Passenger Car Speeds with PCMS at 750 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	22	76	61.6	6.6
Speed at Sensor 2	31	74	60.5	6.3
Speed at Sensor 3	26	74	59.9	7.0
Speed at Sensor 4	17	74	59.1	7.7
Speed at Sensor 5	23	74	57.8	7.2
Speed at Sensor 6	23	71	55.7	6.9
Speed at Sensor 7	23	71	55.0	7.0

Note: STD-Standard Deviation

The passenger car speed profile model for Situation 1 was developed using the passenger car speed measurements at the locations of seven sensors. In the SPSS software, the command of Curve Estimation in Regression was used to generate the model that could be used to best fit the speed data. The model selection process was the same as one in Chapters 5 and 6. According to the R square value of each model, the Cubic model was the best fit. The Cubic model of Situation 1 is:

$$Y = 61.454 - 0.002x - 2.437e^{-6}x^2 + 5.333e^{-10}x^3$$

X: Distance between a passenger car location and the Sensor 1 Location ($1 \leq x \leq$ 1,500 ft)

Y: Vehicle speed

The passenger car speed profile curve and mean speeds at the locations of seven sensors for Situation 1 were presented in Figure 7.1.

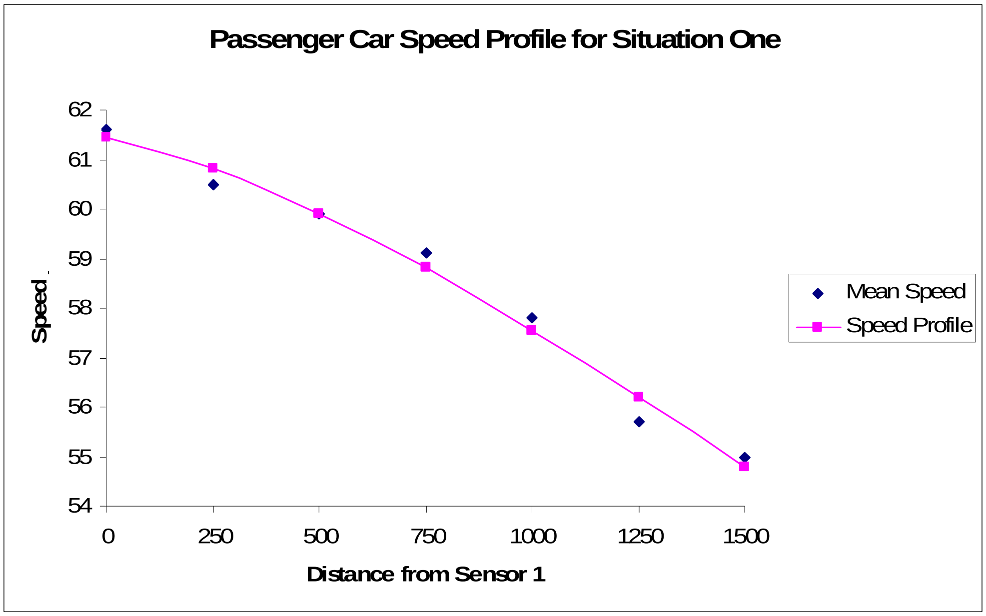


Figure 7.1 Passenger car speed profile curve for Situation One

7.2.1.2 Truck Speed Profile Model for Situation One

When the PCMS was placed at 750 ft upstream of the W20-1 sign, 345 truck speed data were collected in the field experiments as shown in Table 7.1. Table 7.3 shows the descriptive statistics of truck speeds recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor are listed.

Table 7.3 Descriptive Statistics of Truck Speeds with PCMS at 750 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	26	72	58.9	6.6
Speed at Sensor 2	26	71	57.9	6.3
Speed at Sensor 3	27	71	57.4	7.0
Speed at Sensor 4	28	71	57.0	7.7
Speed at Sensor 5	28	71	55.6	7.2
Speed at Sensor 6	28	68	53.9	6.9
Speed at Sensor 7	29	70	53.1	7.0

Note: STD-Standard Deviation

The truck speed profile model for Situation 1 was developed using the truck speed measurements at the locations of seven sensors. The model development process was the same as the one in section 7.2.1.1. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 58.756 - 0.002x - 1.332e^{-6}x^2 + 9.49e^{-14}x^3$$

X: Distance between a truck location and the Sensor 1 Location ($1 \leq x \leq 1{,}500$ ft)

Y: Vehicle speed

The truck speed profile curve and mean speeds at the locations of seven sensors for Situation 1 were presented in Figure 7.2.

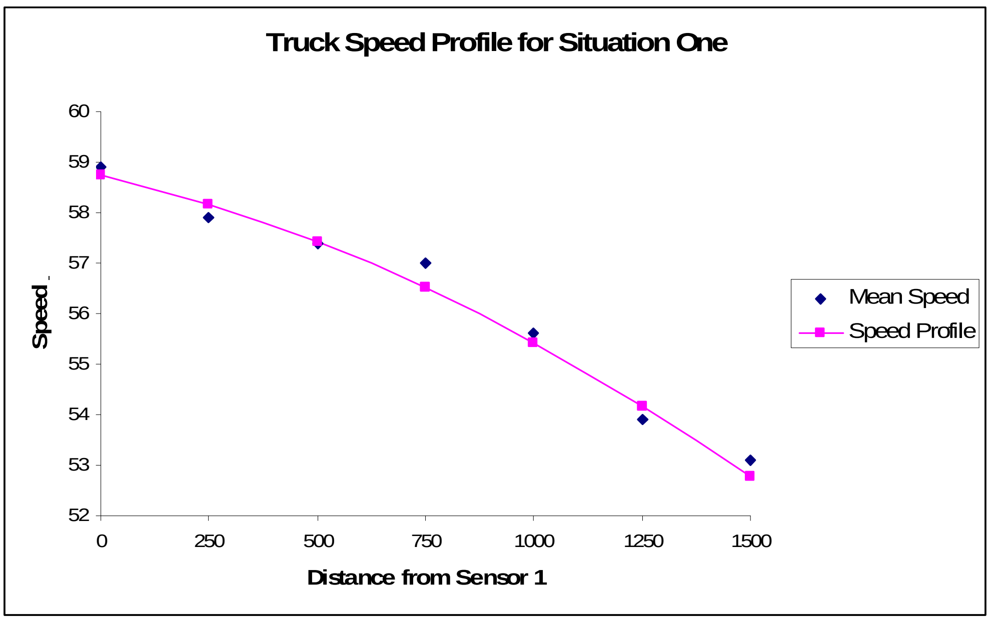


Figure 7.2 Truck speed profile curve for Situation One

7.2.1.3 Determining the Difference of Speed Reduction between Passenger Cars and Trucks for Situation One

When the PCMS was placed at 750 ft upstream of the W20-1 sign, 799 passenger car and 345 truck speed data were collected in the field experiments. In sections 7.2.1.1

and 7.2.1.2, the speed profile models were developed. Figure 7.3 shows the two speed profile curves for Situation 1. As shown in Figure 7.3, the speed profile curves indicated that both passenger cars and trucks slowed down smoothly and consistently in the upstream of the work zone.

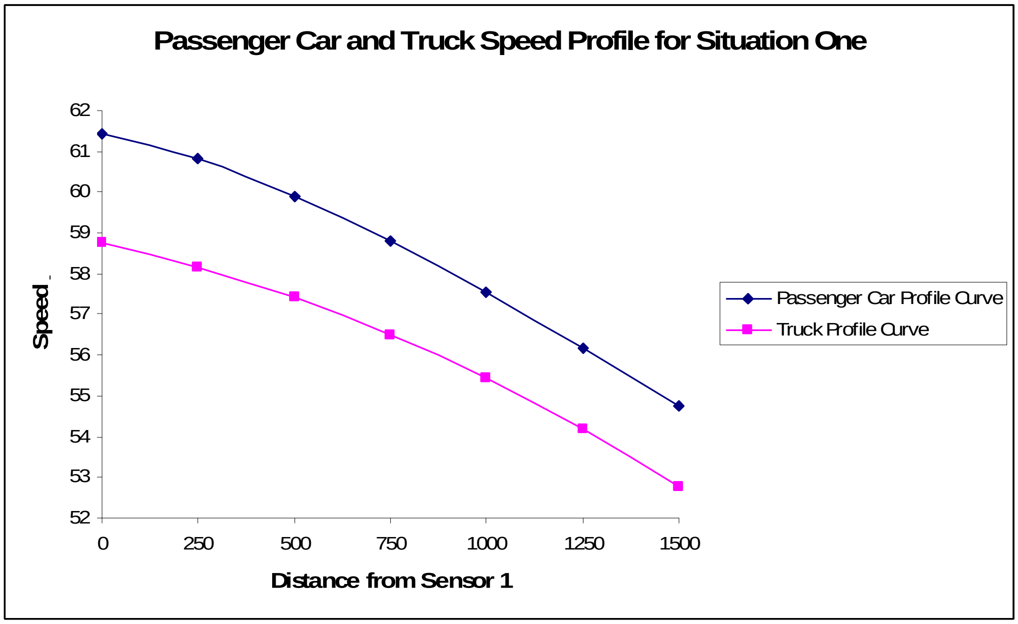


Figure 7.3 Passenger car and truck speed profile curves for Situation One

To determine the difference of speed reductions between passenger cars and trucks, the Levene's test and t-test were conducted using the measured speed data at seven sensor locations. The Levene's test was introduced in section 5.3.1. The t-test was used to compare the measured mean passenger car speed with the measured mean truck speed at seven senor locations. For an example, at the location of Sensor 1, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 1)

$$H_0: \mu_P = \mu_T$$

$$H_1: \mu_P \neq \mu_T$$

Where μ_P and μ_T = measured mean passenger car speed and measured mean truck speed at the Sensor 1 location, respectively, when the PCMS was placed 750 ft away from the W20-1 sign. The null hypothesis was interpreted as the measured mean passenger car speed was equal to the measured mean truck speed. The alternative hypothesis was interpreted as the measured mean passenger car speed was not equal to the measured mean truck speed at the Sensor 1 location. A 5% (0.05) level of confidence was used in the t-test. Since the P-values of Levene's tests would indicate the speed variance between the two populations were equal or not, accordingly, the t-test with equal or unequal variances could be used for analysis. Table 7.4 shows the results of Levene's tests and t-tests for Situation 1.

As shown in Table 7.4, the results of Levene's tests indicated that the passenger cars and trucks had equal speed variances at the locations of Sensors 3, 4, 5, and 7. At all seven senor locations, the measured mean speeds of passenger cars were larger than the measured mean speeds of trucks based on the results of t-tests. The difference of mean speeds ranged from 1.8 mph to 2.6 mph over 1,500 ft distance. Compared with the curves in Figure 7.3, the speed difference between passenger cars and trucks reduced when they were approaching the work zone. The results indicated that though both passenger cars and trucks slowed down when the PCMS was placed at 750 ft away from W20-1, the significant differences of mean speeds (speed variations) between them could spark the cause of vehicle crashes.

Table 7.4 Levene's Test and t-test of Measured Passenger Car and Truck Speeds for Situation One

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances not assumed	3.85	.050	5.785	601.092	.000	2.637	.456	1.742	3.532
Speed at Sensor2	Equal variances not assumed	5.352	.021	5.938	583.634	.000	2.649	.446	1.773	3.525
Speed at Sensor3	Equal variances assumed	2.488	.115	5.377	1142	.000	2.486	.462	1.579	3.392
Speed at Sensor4	Equal variances assumed	.374	.541	4.196	1142	.000	2.085	.497	1.110	3.060
Speed at Sensor5	Equal variances assumed	1.372	.242	4.763	1142	.000	2.256	.474	1.327	3.185
Speed at Sensor6	Equal variances not assumed	4.366	.037	3.757	599.079	.000	1.789	.476	.854	2.724
Speed at Sensor7	Equal variances assumed	2.141	.144	4.131	1142	.000	1.930	.467	1.013	2.847

7.2.2 Passenger Car and Truck Speed Profile Model for Situation Two

7.2.2.1 Passenger Car Speed Profile Model for Situation Two

When the PCMS was placed at 575 ft upstream of the W20-1 sign, 761 passenger car speed data were collected in the field experiments. Table 7.5 shows the descriptive statistics of passenger car speed data recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor location are listed.

Table 7.5 Descriptive Statistics of Passenger Car Speeds with PCMS at 575 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	30	82	63.1	6.8
Speed at Sensor 2	31	78	59.2	7.0
Speed at Sensor 3	29	82	59.2	7.4
Speed at Sensor 4	26	80	58.6	8.1
Speed at Sensor 5	30	76	56.6	8.2
Speed at Sensor 6	23	70	52.7	7.3
Speed at Sensor 7	21	74	52.1	7.1

Note: STD-Standard Deviation

The passenger car speed profile model for Situation 2 was developed using the passenger car speed measurements at the locations of seven sensors. The model development process was the same as the one in section 7.2.1. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 62.542 - 0.01x + 6.51e^{-6}x^2 - 3.381e^{-9}x^3$$

X: Distance between a passenger car location and the Sensor 1 Location ($1 \leq x \leq$ 1,500 ft)

Y: Vehicle speed

The passenger car speed profile curve and mean speeds at the locations of seven sensors for Situation 2 were presented in Figure 7.4.

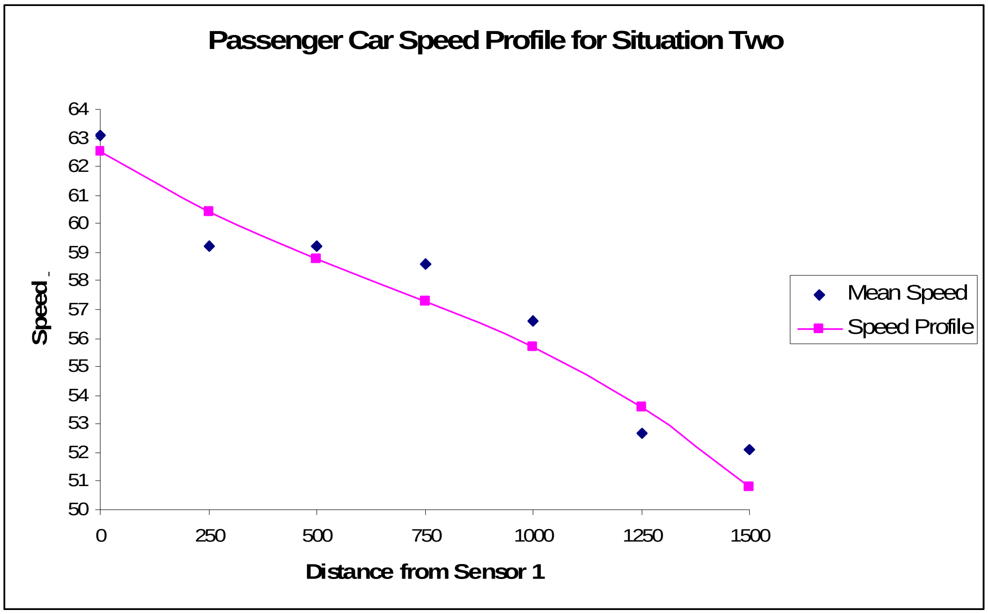


Figure 7.4 Passenger car speed profile curve for Situation Two

7.2.2.2 Truck Speed Profile Model for Situation Two

When the PCMS was placed at 575 ft upstream of the W20-1 sign, 364 truck speed data were collected in the field experiments. Table 7.6 shows the descriptive statistics of truck speed data recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor location are listed.

Table 7.6 Descriptive Statistics of Truck Speeds with PCMS at 575 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	37	78	62.0	5.8
Speed at Sensor 2	35	72	57.2	6.0
Speed at Sensor 3	36	76	58.6	6.6
Speed at Sensor 4	35	79	58.3	7.1
Speed at Sensor 5	34	77	56.1	7.2
Speed at Sensor 6	32	74	52.0	6.7
Speed at Sensor 7	31	71	51.5	6.7

Note: STD-Standard Deviation

The truck speed profile model for Situation 2 was developed using the truck speed measurements at the locations of seven sensors. The model development and selection process was the same as the one in the last subsection. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 61.175 - 0.01x + 9.333e^{-6}x^2 - 4.975e^{-9}x^3$$

X: Distance between a truck location and the Sensor 1 Location ($1 \leq x \leq 1{,}500$ ft)

Y: Vehicle speed

The truck speed profile curve and mean speeds at the locations of seven sensors for Situation 2 were presented in Figure 7.5.

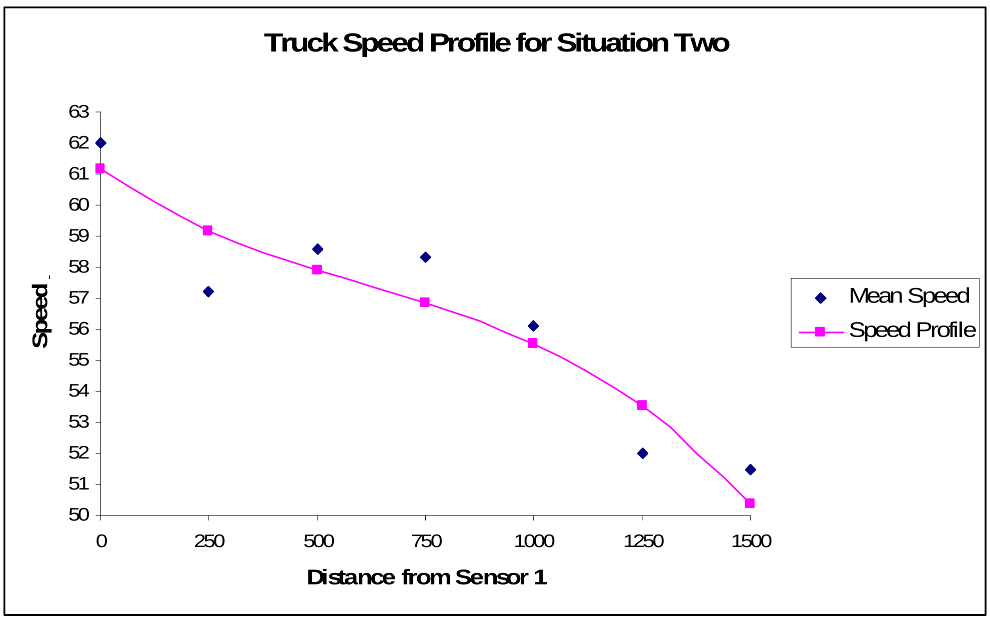


Figure 7.5 Truck speed profile curve for Situation Two

7.2.2.3 Determining the Difference of Speed Reduction between Passenger Cars and Trucks for Situation Two

When the PCMS was placed at 575 ft upstream of the W20-1 sign, 761 passenger car and 364 truck speed data were collected in the field experiments. In sections 7.2.2.1

and 7.2.2.2, the speed profile models were developed for Situation 2. Figure 7.6 shows the two curves for Situation 2. As shown in Figure 7.6, the speed profile curves indicated that both passenger cars and trucks slowed down smoothly and consistently.

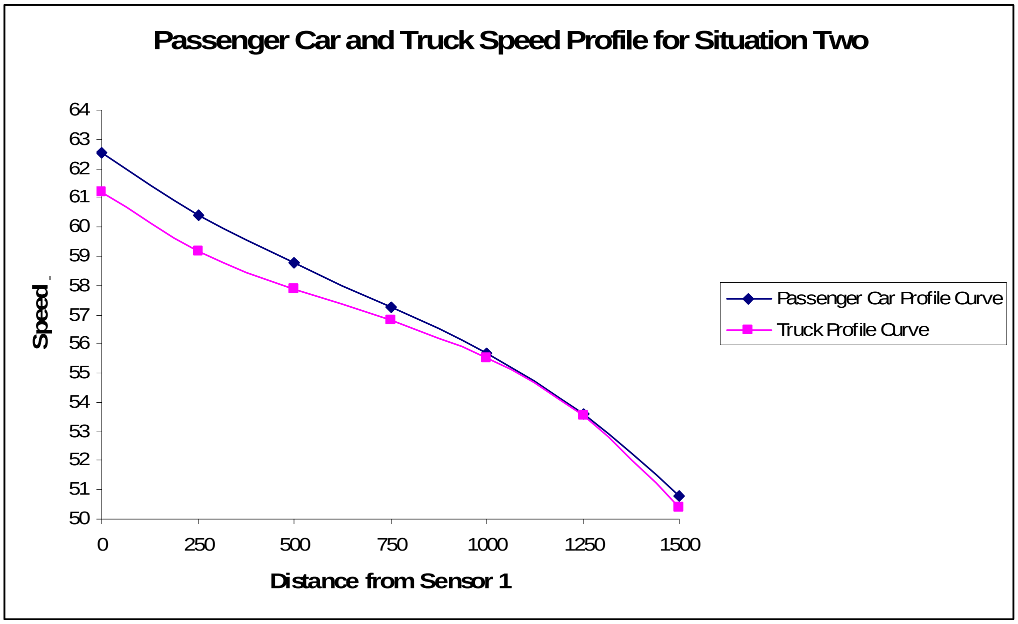


Figure 7.6 Passenger car and truck speed profile curves for Situation Two

To determine the difference of speed reductions between passenger cars and trucks, the Levene's test and t-test were conducted using the measured speed data at seven sensor locations. For Situation 2, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 2)

$$H_0: \mu_P = \mu_T$$

$$H_1: \mu_P \neq \mu_T$$

Where μ_P and μ_T = measured mean passenger car speed and measured mean truck speed at the Sensor 1 location, respectively, when the PCMS was placed 575 ft away from the W20-1 sign. The null hypothesis was interpreted as the measured mean passenger car speed was equal to the measured mean truck speed at the Sensor 1 location. The alternative hypothesis was interpreted as the measured mean passenger car speed was not equal to the measured mean truck speed at the Sensor 1 location. A 5% (0.05) level of confidence was used in the t-test. Table 7.7 shows the results of Levene's tests and t-tests at all seven sensor locations for Situation 2. As shown in Table 7.7, the results of Levene's tests indicated that the passenger cars and trucks had equal speed variance only at the location of Sensor 7. At the first two senor locations, the measured mean speeds of passenger cars were larger than those of trucks based on the results of t-tests. Then started at the Sensor 3 location, there was no significant difference between the mean speeds of passenger cars and trucks. The mean speeds differences changed from 1.0 mph to 2.0 mph from the Sensor 1 location to Sensor 2 location. Compared with the curves in Figure 7.6, the speed difference between passenger cars and trucks reduced when vehicles were approaching the work zone. The results indicated that both passenger cars and trucks slowed down and reached at an equivalent speed at the Sensor 3 location when the PCMS was placed at 575 ft away from W20-1. Compared with the Situation 1, the Situation 2 was safer for vehicles in the upstream of a work zone because the traveling distance with significant speed difference between passenger cars and trucks was reduced.

Table 7.7 Levene's Test and t-test of Measured Passenger Car and Truck Speeds for Situation Two

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances not assumed	9.907	.002	2.783	824.126	.006	1.095	.393	.323	1.867
Speed at Sensor2	Equal variances not assumed	11.576	.001	4.803	828.586	.000	1.951	.406	1.154	2.748
Speed at Sensor3	Equal variances not assumed	9.497	.002	1.329	805.048	.184	.582	.438	-.278	1.441
Speed at Sensor4	Equal variances not assumed	8.766	.003	.799	806.124	.425	.379	.474	-.552	1.310
Speed at Sensor5	Equal variances not assumed	10.237	.001	1.002	808.998	.317	.483	.482	-.463	1.428
Speed at Sensor6	Equal variances not assumed	3.925	.048	1.568	773.546	.117	.692	.441	-.174	1.559
Speed at Sensor7	Equal variances assumed	1.352	.245	1.368	761.200	.172	.594	.434	-.258	1.445

7.2.3 Passenger Car and Truck Speed Profile Model for Situation Three

7.2.3.1 Passenger Car Speed Profile Model for Situation Three

When the PCMS was placed at 400 ft upstream of the W20-1 sign, 652 passenger car speed data were collected in the field experiments. Table 7.8 shows the descriptive statistics of passenger car speed data recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor are listed.

Table 7.8 Descriptive Statistics of Passenger Car Speeds with PCMS at 400 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	30	78	62.1	6.5
Speed at Sensor 2	25	76	60.8	6.9
Speed at Sensor 3	25	77	60.0	7.5
Speed at Sensor 4	26	81	59.3	8.4
Speed at Sensor 5	28	76	57.9	8.9
Speed at Sensor 6	26	70	54.4	7.8
Speed at Sensor 7	25	71	53.6	7.4

Note: STD-Standard Deviation

The passenger car speed profile model for Situation 3 was developed using the passenger car speed measurements at the locations of seven sensors. The model development process was the same as the one in last subsection. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 61.892 - 0.002x - 2.363e^{-6}x^2 + 1.013e^{-12}x^3$$

X: Distance between a passenger car location and the Sensor 1 Location ($1 \leq x \leq 1{,}500$ ft)

Y: Vehicle speed

The passenger car speed profile curve and mean speeds at the locations of seven sensors for Situation 3 were presented in Figure 7.7.

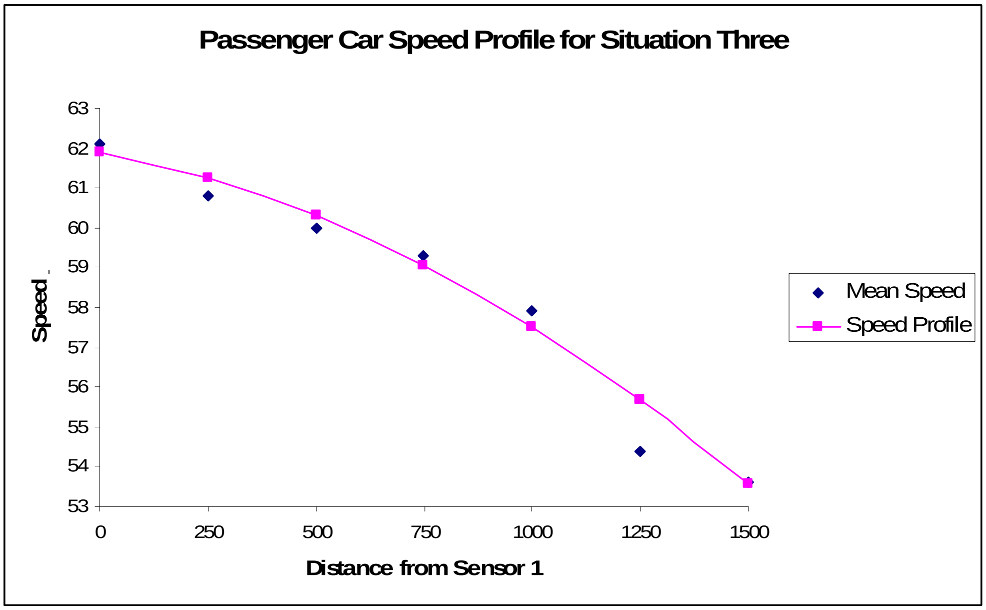


Figure 7.7 Passenger car speed profile curve for Situation Three

7.2.3.2 Truck Speed Profile Model for Situation Three

When the PCMS was placed at 400 ft upstream of the W20-1 sign, 344 truck speed data were collected in the field experiments. Table 7.9 shows the descriptive statistics of truck speed data recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor are listed.

Table 7.9 Descriptive Statistics of Truck Speeds with PCMS at 400 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	34	71	58.9	6.2
Speed at Sensor 2	32	71	57.7	6.5
Speed at Sensor 3	23	72	57.5	7.1
Speed at Sensor 4	30	73	57.7	7.6
Speed at Sensor 5	25	73	56.9	7.7
Speed at Sensor 6	22	67	53.9	7.2
Speed at Sensor 7	24	66	52.6	7.0

Note: STD-Standard Deviation

The truck speed profile model for Situation 3 was developed using the truck speed measurements at the locations of seven sensors. The model development process was the same as the one in the last section. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 58.698 - 0.003x + 4.462e^{-6}x^2 - 3.379e^{-9}x^3$$

X: Distance between a passenger car location and the Sensor 1 Location ($1 \leq x \leq$ 1,500 ft)

Y: Vehicle speed

The truck speed profile curve and mean speeds at the locations of seven sensors for Situation 3 were presented in Figure 7.8.

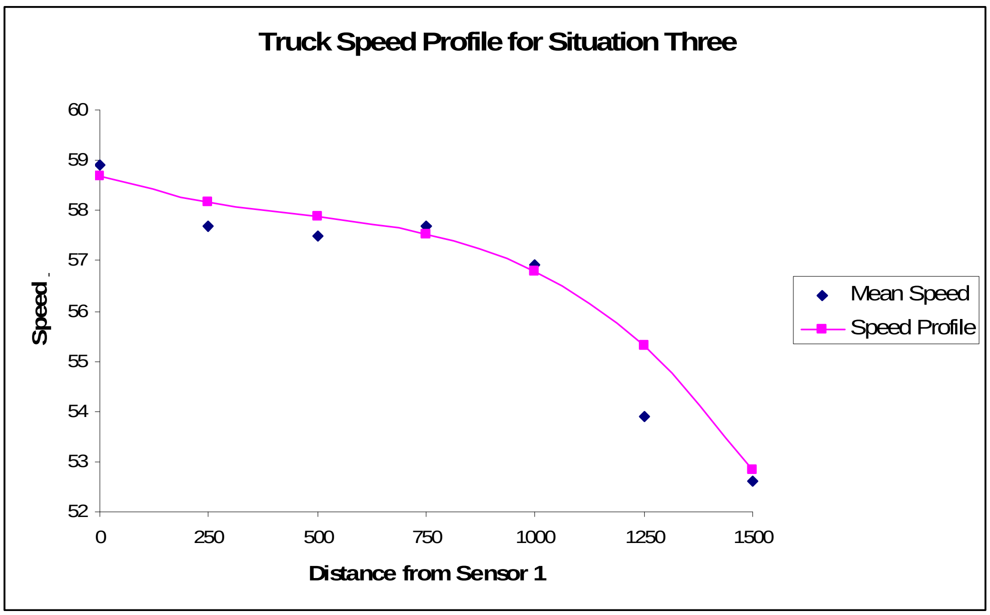


Figure 7.8 Truck speed profile curve for Situation Three

7.2.3.3 Determining the Difference of Speed Reduction between Passenger Cars and Trucks for Situation Three

When the PCMS was placed at 400 ft upstream of the W20-1 sign, 652 passenger car and 344 truck speed data were collected in the field experiments. In sections 7.2.3.1 and 7.2.3.2, the speed profile models were developed for Situation 3 as shown in Figure 7.9. As shown in Figure 7.9, the speed profile curves indicated that both passenger cars and trucks slowed down smoothly and consistently.

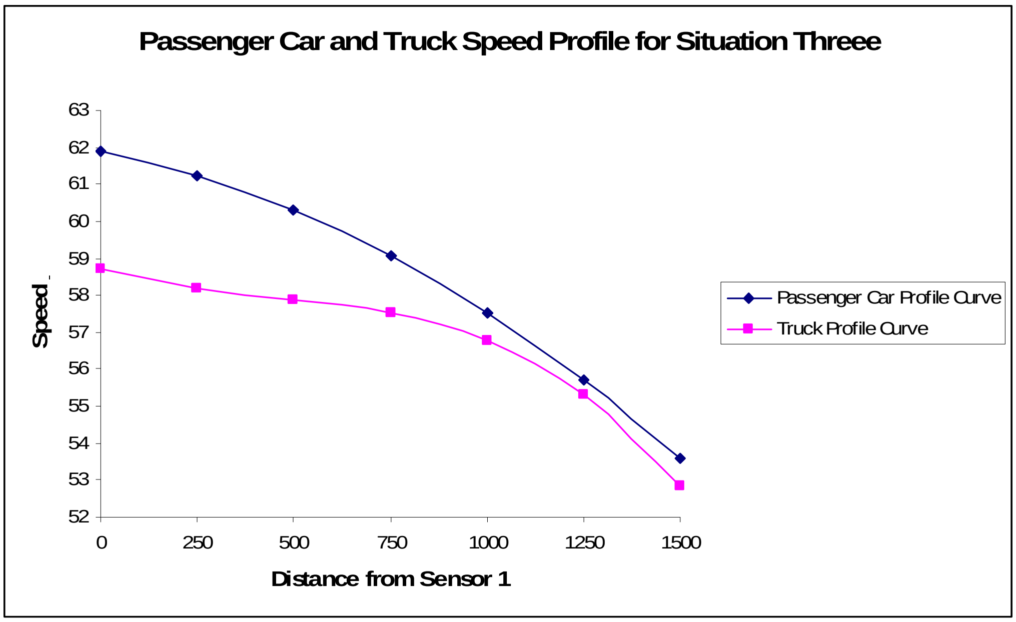


Figure 7.9 Passenger car and truck speed profile curves for Situation Three

To determine the difference of speed reductions between passenger cars and trucks, the Levene's test and t-test were conducted using the measured speeds at seven sensor locations. For Situation 3, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 3)

$$H_0: \mu_P = \mu_T$$

$$H_1: \mu_P \neq \mu_T$$

Where μ_P and μ_T = measured mean passenger car speed and measured mean truck speed at the Sensor 1 location, respectively, when the PCMS was placed 400 ft away from the W20-1 sign. The null hypothesis was interpreted as the measured mean passenger car speed was equal to the measured mean truck speed at the Sensor 1 location. The alternative hypothesis was interpreted as the measured mean passenger car speed was not equal to the measured mean truck speed at the Sensor 1 location. A 5% (0.05) level of confidence was used in the t-test. Table 7.10 shows the results of Levene's tests and t-tests at all seven sensor locations for Situation 3.

As shown in Table 7.10, the results of Levene's tests indicated that the passenger cars and trucks had equal speed variances at the locations of Sensor 1, 2, 3, and 7. Only at the Sensor 6 location, the measured mean speed of passenger cars was equal to the one of trucks based on the results of t-tests. The mean speed differences changed from 3.2 mph to 1.1 mph from the Sensor 1 location to Sensor 5 location. Compared with the curves in Figure 7.9, the measured mean speed difference between passenger cars and trucks reduced when vehicles were approaching the work zone till to the Sensor 6 location where they reached an equal speed, however, the measured mean speed difference became significant different at the Sensor 7 location. Compared with the Situation 2, the Situation 3 was not safer for vehicles in the upstream of a work zone because the traveling distance with significant speed difference between passenger cars and trucks was increased.

Table 7.10 Levene's Test and t-test of Measured Passenger Car and Truck Speeds for Situation Three

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances assumed	.633	.427	7.571	994	.000	3.213	.424	2.38	4.046
Speed at Sensor2	Equal variances assumed	2.161	.142	6.789	994	.000	3.076	.453	2.187	3.965
Speed at Sensor3	Equal variances assumed	2.438	.119	5.269	994	.000	2.588	.491	1.624	3.552
Speed at Sensor4	Equal variances not assumed	5.178	.023	3.065	784.217	.002	1.605	.542	.577	2.633
Speed at Sensor5	Equal variances not assumed	9.116	.003	1.998	784.217	.046	1.084	.542	.019	2.148
Speed at Sensor6	Equal variances not assumed	5.136	.024	1.074	741.183	.283	.532	.495	-.440	1.503
Speed at Sensor7	Equal variances assumed	3.147	.076	2.199	994	.028	1.069	.486	.115	2.024

7.3 SUMMARY

Truck related crashes contribute to a significant percentage of motor vehicle crashes, which often result in fatalities and injuries. There was a significant increase in crash severity when a truck crash occurred in the work zones. To mitigate the prominent high crash rate and severity of truck-related crashes in the work zones, the effectiveness of a PCMS was tested on reducing passenger car and truck speeds in the upstream of work zones. Due to the difference of driving behaviors between passenger car drivers and truck drivers, it was necessary to study the truck speed profile models and passenger car speed profile models separately

In this chapter, the truck and passenger car speed profile models were developed separately for three situations: 1) PCMS at 750 ft away from the W20-1 sign; 2) PCMS at 575 ft away from the W20-1 sign; 3) PCMS at 400 ft away from the W20-1 sign. When the PCMS was placed at 750 ft away from the W20-1 sign in the upstream of the work zone, at all seven senor locations, the measured mean speeds of passenger cars were larger than the measured mean speeds of trucks. The results indicated that though both passenger cars and trucks slowed down, the significant differences of mean speeds between them could spark the cause of vehicle crashes. When the PCMS was placed at 400 ft away from the W20-1 sign in the upstream of the work zone, both of passenger cars and trucks slowed down and reached equal speed at the Sensor 6 location, the significant mean speed differences occurred at most locations indicated a higher probability of crashes.

When the PCMS was placed at 575 ft away from the W20-1 sign in the upstream of the work zone, both of passenger cars and trucks slowed down and reached equal speed at the Sensor 3 location. Compared with the Situation 1 and 3, the Situation 2 was the safest for vehicles in the upstream of a work zone because the traveling distance with significant speed differences was reduced. Therefore, it was proved again that the optimal deployment range of a PCMS in the upstream of a work zone should be near 575 ft away from the W20-1 sign.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

Highway work zone safety has been a concern for decades. The rural highways account for a major portion in highway systems in the United States. To improve the safety of rural highway work zones, numerous traffic control devices and safety countermeasures have been developed and implemented. A Portable Changeable Message Sign (PCMS), sometimes referred to as a Changeable Message Sign (CMS), a Variable Message Sign (VMS) or a Dynamic Message Sign (DMS), is a traffic control device capable of displaying various messages to inform motorists of unusual driving conditions. It is a supplemental device to standard traffic control signs. Regarding the deployment of a PCMS in rural highway work zones, there is no specific guideline in the latest version of MUTCD. Traffic engineers have to make decisions based on their knowledge and experiences. This research was aimed to provide valuable insights on effectively utilizing a PCMS in rural highway work zones by determining the optimal deployment location of the PCMS. To achieve the objectives, the author has conducted the following tasks including: 1) reviewing the literature; 2) designing field experiments and survey; 3) conducting field experiments and survey, and 4) performing data analyses. The results of this research hold great potential to improve the safety of rural highway work zones by optimally deploying the PCMS in the upstream of work zones.

8.1 CONCLUSIONS

The conclusions were drawn based on the results of data analyses from three field experiments and survey. Details of the data analyses could be found in Chapters 4, 5, and 6. The following are major conclusions of this research:

1. The PCMS was effective on reducing vehicle speeds in the upstream of one-lane two-way rural highway work zones. Vehicle speeds were reduced by 4.7 mph over an average distance of 500 ft when the PCMS was on. When the PCMS was off but still visible, the vehicle speeds reduced 3.3 mph over an average distance of 500 ft. A 1.9 mph speed reduction occurred over an average distance of 500 ft when the PCMS was absent.

2. The PCMS was effective on reducing passenger car and truck speeds in the upstream of one-lane two-way rural highway work zones. When the PCMS was on, passenger car speeds were reduced by 4.0 mph and truck speeds were reduced by 5.0 mph over a distance of 500 ft. When the PCMS was off, passenger car speeds were reduced by 2.3 mph and truck speeds were reduced by 4.0 mph over a distance of 500 ft. When the PCMS was absent, passenger car speeds declined by 3.0 mph, and truck speeds declined by 1.0 mph over a distance of 500 ft.

3. The deployment location of a PCMS had a significant impact on vehicle speed reduction. There were 3 mph, 8 mph, and 5 mph mean vehicle speed reductions when the PCMS was placed 1,250 ft, 750 ft, and 250 ft away from the first TTC sign (W20-1 sign) in the upstream of one-lane two-way rural highway work zones, respectively.

4. The deployment location of a PCMS had an impact on drivers' behaviors when they were approaching work zones. When the PCMS was placed at 1,250 ft and 250 ft away from the W20-1 sign, the up-down speed changes shown on the curves of mean vehicle speed indicated that speed reductions were not consistent under these two conditions, and thus it would increase the probability of vehicle crashes.

5. The vehicle speed profiles could be best described using the cubic models. The speed profile models were keys to understand vehicle speed changes and they were used to determine the optimal deployment range of a PCMS in the upstream of work zones.

6. The optimal deployment range of a PCMS was from 556 ft to 575 ft away from the first TTC sign in the upstream of a work zone. This range was derived from measured speeds and speed profile models.

7. A majority of drivers were able to recognize the messages displayed on the PCMS and recommended the implementation of a PCMS in the upstream of the work zones in addition to the existing traffic signs. The PCMS had a better effect on female drivers than male drivers. Driving different types of vehicles did not make a difference on drivers' understanding of messages.

8. Trucks and passenger cars had different speed profile models in the upstream of the work zones. When the PCMS was placed 575 ft away from the W20-1 sign, the traveling distance with significant speed difference between trucks and passenger cars was reduced most which was helpful on reducing the probability of vehicle crashes in the upstream of work zones.

8.2 RECOMMENDATIONS

The following recommendations are suggested for implementing the results of this research project and future research.

1. The PCMS was effective on reducing vehicle speeds in the upstream of work zones if it was used properly. The results of field experiments indicated that if the PCMS was not properly placed, the vehicle speeds would fluctuate thus increased the probability of vehicle crashes. To maximize the benefits of utilization of a PCMS in the work zones,

it is recommended that the optimal deployment range of a PCMS shall be incorporated in the MUTCD.

2. The optimal deployment range of a PCMS in the upstream of a work zone was determined using two specific text messages. Future research is needed to determine whether the optimal deployment range will be different if using other text messages.

3. Currently, the PCMS was utilized to convey text messages to motorists. However, the physical condition differences among drivers make it difficult to expect the same effect on all drivers. For instance, older drivers might take a longer time to capture text messages displayed on the PCMS. Thus, there is a need to investigate the possibility of using graphics to convey information.

4. In this research project, the PCMS was placed in the upstream of the work zones. Future research is needed to determine the optimal deployment range for a PCMS installed in the other areas of a work zone. These areas included the advance warning area, the transition area, the activity area, and the termination area.

5. The results of the survey showed that male drivers were more likely to not take actions in responding to the messages displayed on the PCMS compared with those of female drivers. There is a need to develop a work zone education program for drivers to raise their awareness of highway work zone risks.

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APPENDIX I: A SAMPLE OF SURVEY FORM

1: Did you see the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?

Yes ______ No ______

<u>If the answer is YES, then, continue the survey. If the answer is NO, stop the survey.</u>

2: Did you understand the messages displayed on the PCMS?

Yes ______ No ______

3: What actions did you take after you saw the PCMS?

Slow down ______ Look for more information ______

Do nothing ______ Take other actions _____________

4: Did you think that the PCMS drew your attention more to the work zone traffic condition?

Yes ______ No ______

5: Do you prefer the use of a PCMS to alert drivers about the upcoming work zones in addition to the existing sign  ?

Yes ______ No ______

APPENDIX II: A PORTION OF THE SPEED DATASHEET FOR EXPERIMENT PHASE I

No.	LENGTH1	MPH1	LENGTH2	MPH2	PCMS[a]	Days	Jobsite[b]
1	19	31	19	31	1	0	0
2	20	42	21	26	1	1	0
3	22	29	23	29	1	1	0
4	30	62	19	30	1	0	0
5	27	35	26	31	1	1	0
6	72	35	76	31	1	1	0
7	67	60	61	31	1	3	0
8	69	33	68	33	1	0	0
9	23	39	22	33	1	1	0
10	23	34	22	33	1	1	0
11	20	37	19	36	0	0	0
12	18	39	20	47	0	0	0
13	16	40	19	32	0	1	0
14	19	40	19	37	0	0	0
15	20	40	17	39	0	0	0
16	23	41	22	37	0	1	0
17	17	41	20	45	0	1	0
18	22	42	23	43	0	1	0
19	18	42	18	45	0	2	0
20	26	43	24	37	0	0	0
21	20	65	21	68	2	3	0
22	70	71	66	68	2	3	0
23	18	66	19	69	2	3	0
24	81	69	81	70	2	3	0
25	19	66	21	72	2	3	0
26	65	72	67	73	2	3	0
27	17	64	21	73	2	3	0
28	16	66	18	78	2	3	0
29	27	48	24	29	2	4	1
30	18	46	20	31	2	5	1

a: 1 = PCMS On; 0 = PCMS Off; and 2 = PCMS Absent.
b: 0 = US-36 Work Zone and 1 = US-73 Work Zone.

APPENDIX III: A PORTION OF THE SPEED DATASHEET FOR EXPERIMENT PHASE II

No.	Speed1	Speed2	Speed3	Speed4	Speed5	Speed6	Speed7	Length	PCMS[a]
1	66	64	61	62	65	63	61	156	1
2	71	70	70	71	69	65	62	697	1
3	50	50	50	50	51	51	52	116	1
4	55	54	52	51	50	48	47	798	1
5	66	64	63	64	66	64	61	382	1
6	44	42	42	43	44	43	42	133	1
7	53	50	48	46	45	43	41	109	1
8	65	62	60	58	55	51	47	138	1
9	61	61	60	62	61	59	57	139	1
10	63	55	55	55	55	52	51	110	1
11	70	66	66	66	67	63	63	116	2
12	61	59	60	61	61	58	58	386	2
13	68	59	57	57	55	51	49	136	2
14	69	48	68	65	62	58	55	230	2
15	70	44	67	66	66	62	61	132	2
16	58	45	57	58	57	56	56	106	2
17	67	42	66	67	67	63	63	143	2
18	69	44	68	68	67	63	58	549	2
19	62	55	60	65	59	58	58	230	2
20	63	53	57	57	54	51	50	109	2
21	66	66	67	68	67	62	61	120	3
22	68	67	67	65	63	59	60	102	3
23	48	45	43	40	40	40	40	110	3
24	61	58	58	55	53	49	50	117	3
25	63	62	61	60	59	53	52	109	3
26	56	55	54	54	56	53	55	120	3
27	59	58	56	56	58	53	52	263	3
28	59	57	57	58	59	54	53	123	3
29	54	54	55	57	60	57	58	242	3
30	63	60	59	58	59	54	56	117	3

a: 1 = PCMS at 1,250 ft; 2 = PCMS at 750 ft; and 3 = PCMS at 250 ft.

APPENDIX IV: A PORTION OF THE SPEED DATASHEET FOR EXPERIMENT PHASE III

No.	Speed1	Speed2	Speed3	Speed4	Speed5	Speed6	Speed7	Length	PCMS[a]
1	66	63	63	62	60	57	55	112	1
2	55	53	53	51	51	51	52	137	1
3	50	50	50	50	49	48	46	170	1
4	62	59	56	55	54	50	50	396	1
5	56	56	55	55	54	52	51	696	1
6	58	54	51	48	48	46	43	98	1
7	67	64	62	61	61	57	53	630	1
8	59	59	59	58	58	55	54	659	1
9	55	55	54	56	57	54	53	99	1
10	74	72	72	71	72	68	64	129	1
11	69	67	67	69	70	65	64	150	2
12	59	57	58	59	57	53	52	110	2
13	67	63	59	60	58	55	53	151	2
14	62	58	60	61	60	58	57	740	2
15	52	50	51	51	51	47	46	124	2
16	70	67	69	72	71	66	65	773	2
17	70	64	61	56	53	49	48	120	2
18	62	58	59	58	56	52	49	373	2
19	64	61	62	61	59	56	56	114	2
20	69	61	69	66	67	63	61	619	2
21	67	65	59	44	44	46	51	116	3
22	54	54	53	53	52	52	52	118	3
23	60	57	57	54	49	52	53	161	3
24	57	57	59	60	60	56	54	136	3
25	70	70	71	73	67	65	63	111	3
26	69	70	71	71	70	64	63	114	3
27	62	62	60	58	59	53	53	351	3
28	63	62	62	62	64	43	42	139	3
29	58	56	55	54	53	46	47	110	3
30	72	73	70	64	57	50	49	106	3

a: 1 = PCMS at 750 ft; 2 = PCMS at 575 ft; and 3 = PCMS at 400 ft.

APPENDIX V: A PORTION OF THE SURVEY DATASHEET

Time[a]	Weather[b]	Q1	Q2	Q3	Q4	Q5	Vehicle[c]	Sex[d]	No response
1	1	1	1	2	1	1	1	1	
1	1	1	1	1	1	1	1	1	
1	1	1	1	1	1	1	1	1	
1	1	1	2	1	1	1	1	1	
1	1	1	1	2	1	1	1	1	
1	1	1	1	1	1	1	1	1	
1	1	1	1	1	1	1	1	2	
1	1	1	1	1	1	1	1	2	
1	1	1	1	1	1	1	1	2	
2	1	1	1	1&2	1	1	1	1	
2	1	1	1	1	1	1	1	2	
2	1	1	1	1	1	1	2	1	
2	1	1	1	1	1	1	2	1	
2	1	1	1	1	1	1	2	1	
2	1	1	1	1	1	1	1	1	
2	1	1	1	1	1	1	1	1	
2	1	1	1	1	1	1	1	2	
2	1	1	1	1	1	1	1	2	
2	1	1	1	1	1	1	1	1	
2	1	1	1	1	1	1	1	2	
2	1	1	1	1	1	1	2	1	
2	1						1		1

a: 1 = Moring and 2 = Afternoon.
b: 1 = Normal and 2 = Adverse.
c: 1 = Passenger Car and 2 = Truck.
d: 1 = Male and 2 = Female.